



New perspectives on volcanic clouds from the A-Train

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Volcanic clouds: 'dirty thunderstorms'

- **Volcanic eruption cloud**

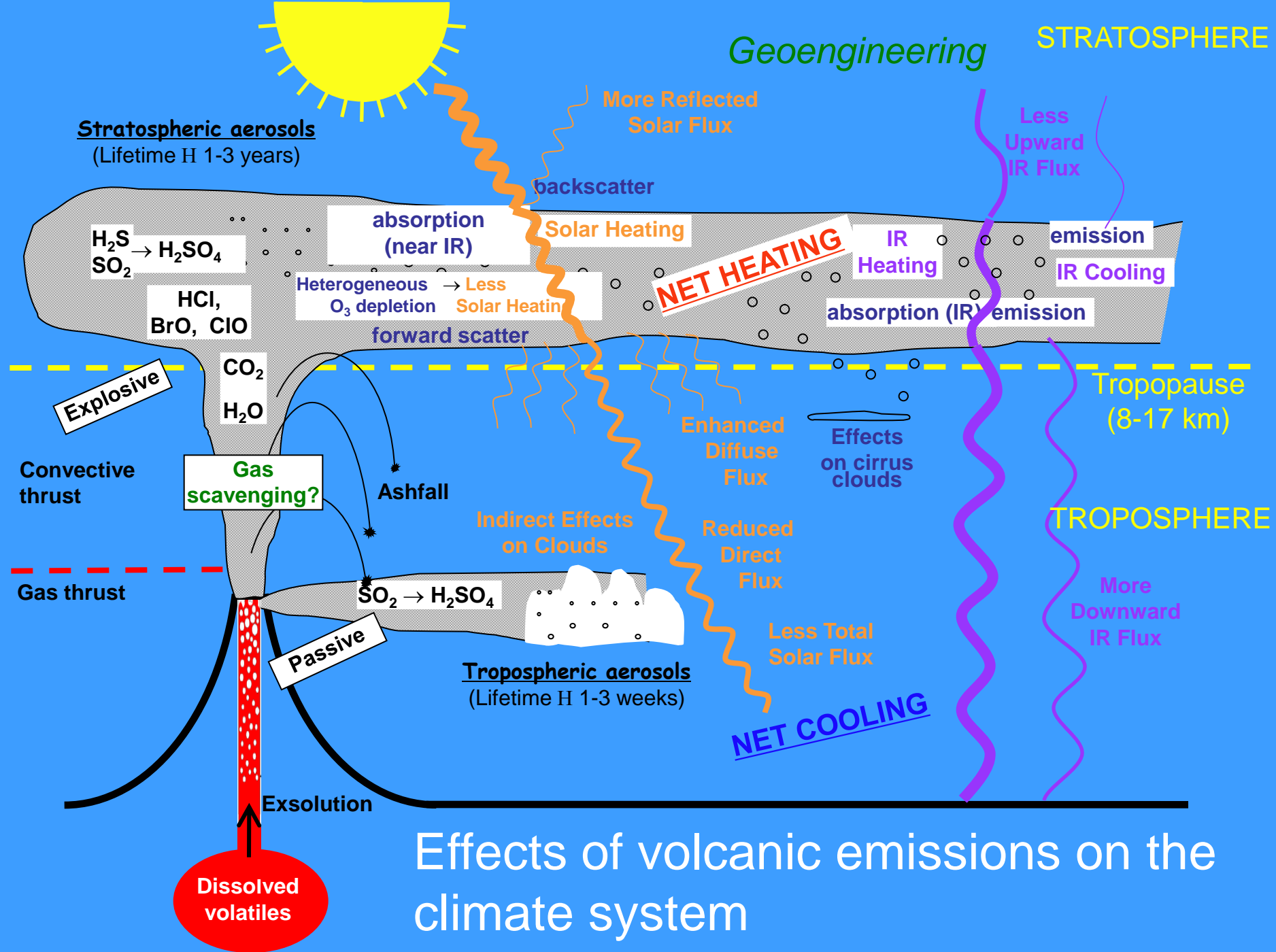
- Vertically extensive
- Short-lived (hours)
- Overshooting top
- Stratospheric penetration
- Lightning
- Umbrella cloud (gravity current)
- 'Overseeded' with ice nuclei (ash)
- Ash (μm – cm), hydrometeors
- Layered structure
- 'Downdraft' during ashfall?



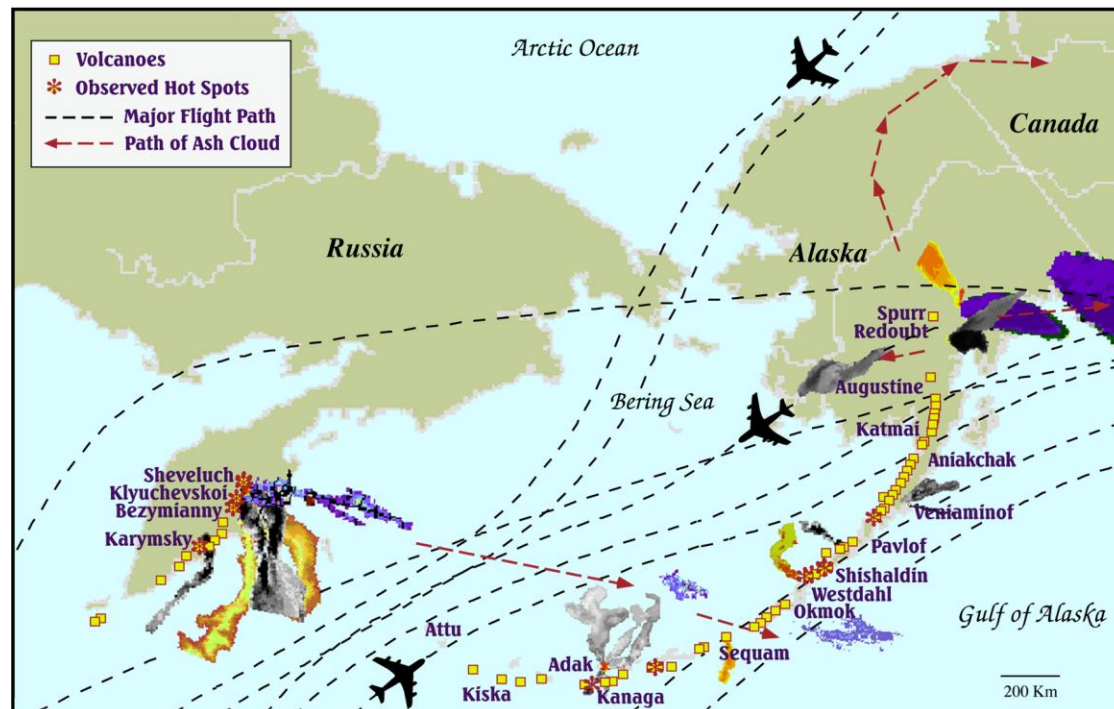
- **Single-cell Cb**

- Vertically extensive
- Short-lived (hours)
- Overshooting top
- Rise to tropopause
- Anvil: ice-rich blow-off
- Hydrometeors (rain – hail)
- Lightning
- Downdrafts

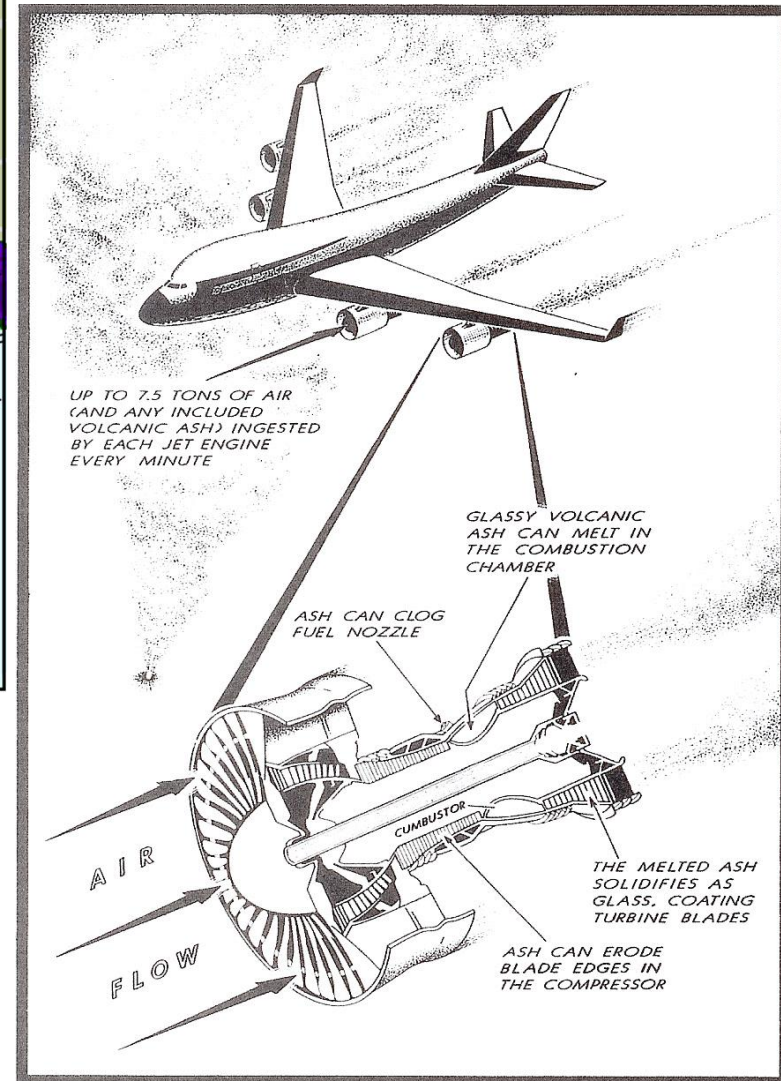




Aviation hazards from volcanic clouds

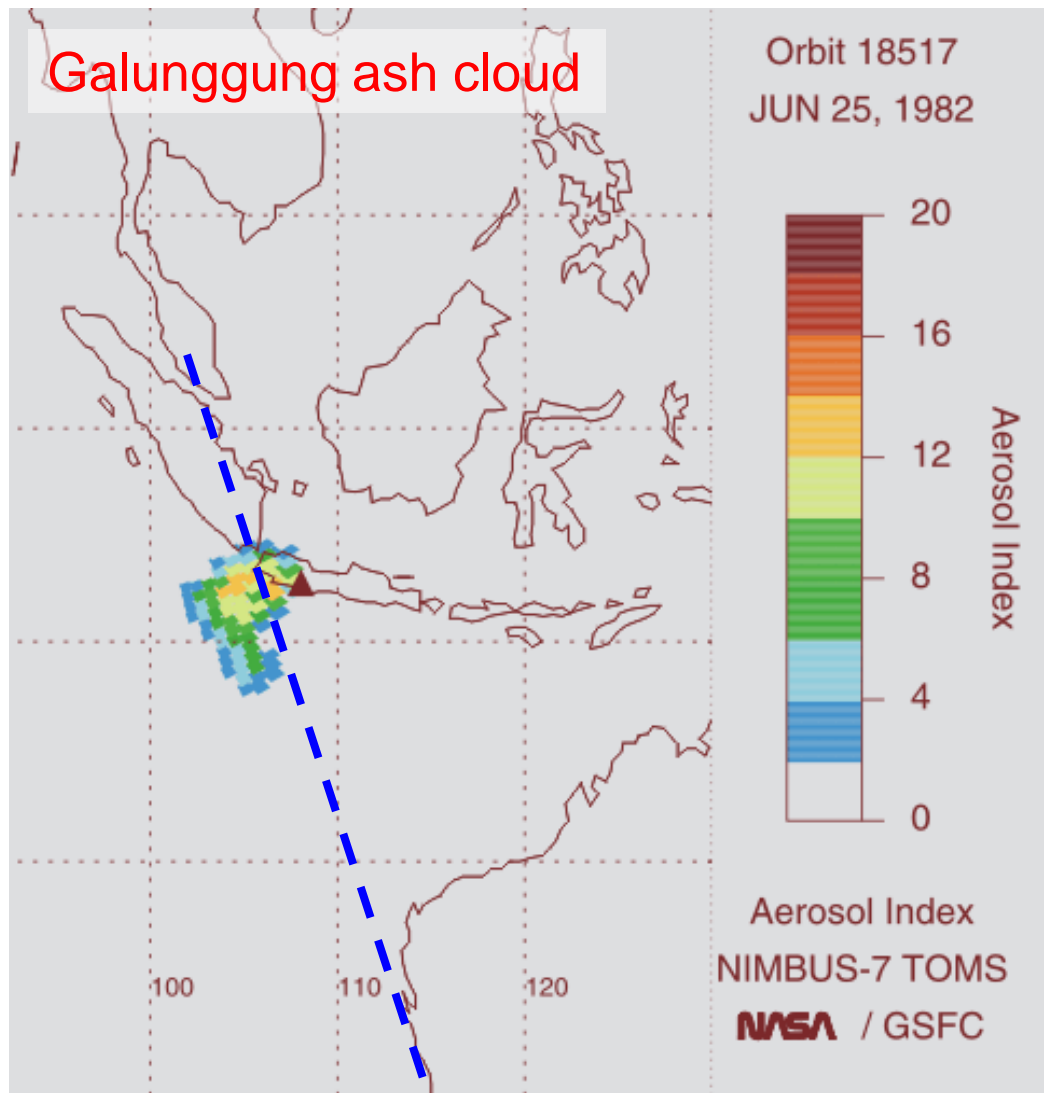


- **Acute hazards**
 - Engine failure due to melted ash
 - Abrasion of windshield
 - Effects on avionics
- **Secondary hazards**
 - Corrosion by ash, sulfuric acid
- **Mitigation**
 - Immediate detection of fresh volcanic clouds
 - Tracking/forecast of cloud position and altitude



From: Volcanoes; Crucibles of Change, Princeton U. Press, Princeton, 1997.

Two near-disastrous volcanic cloud encounters



"Ladies and gentlemen, this is your captain speaking. We have a small problem. All four engines have stopped. We are doing our damndest to get them under control. I trust you are not in too much distress." Capt. Eric Moody, BA Flight 9

~2 g/m³ ash?

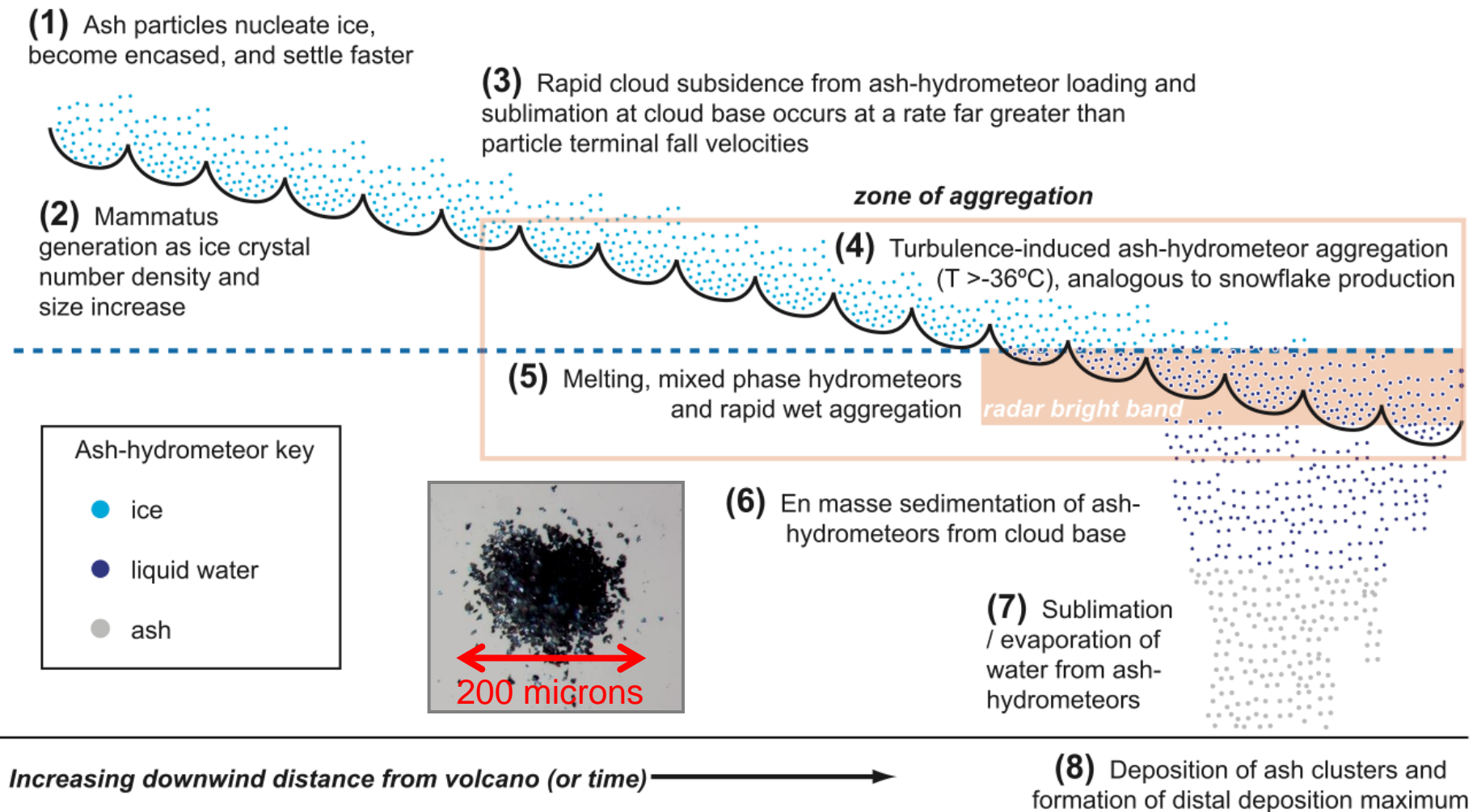
- BA 009 (B747), Kuala Lumpur – Perth, 24 June 1982
- KLM 867 (B747), Amsterdam – Tokyo, 15 December 1989 (Redoubt, AK)

Volcanic ash sedimentation



Mammatus lobes on the Mount St. Helens volcanic cloud over Ephrata, WA, 18 May 1980
(© D. Miller)

Hydrometeor-enhanced sedimentation of volcanic ash



- Ash aggregation prematurely removes fine ash that would be an aviation hazard
- How do we explain secondary ash thickness maxima and ash aggregate fallout?
- Can CloudSat W-band radar detect the bright band?

[Durant et al., JGR, 2009]

Exploiting A-Train synergy for volcanic cloud studies

Aura

OMI - SO_2 , ash, BrO

TES - SO_2

MLS - UTL SO_2 , HCl, IWC

Aqua

MODIS - SO_2 , ash, sulfate, ice

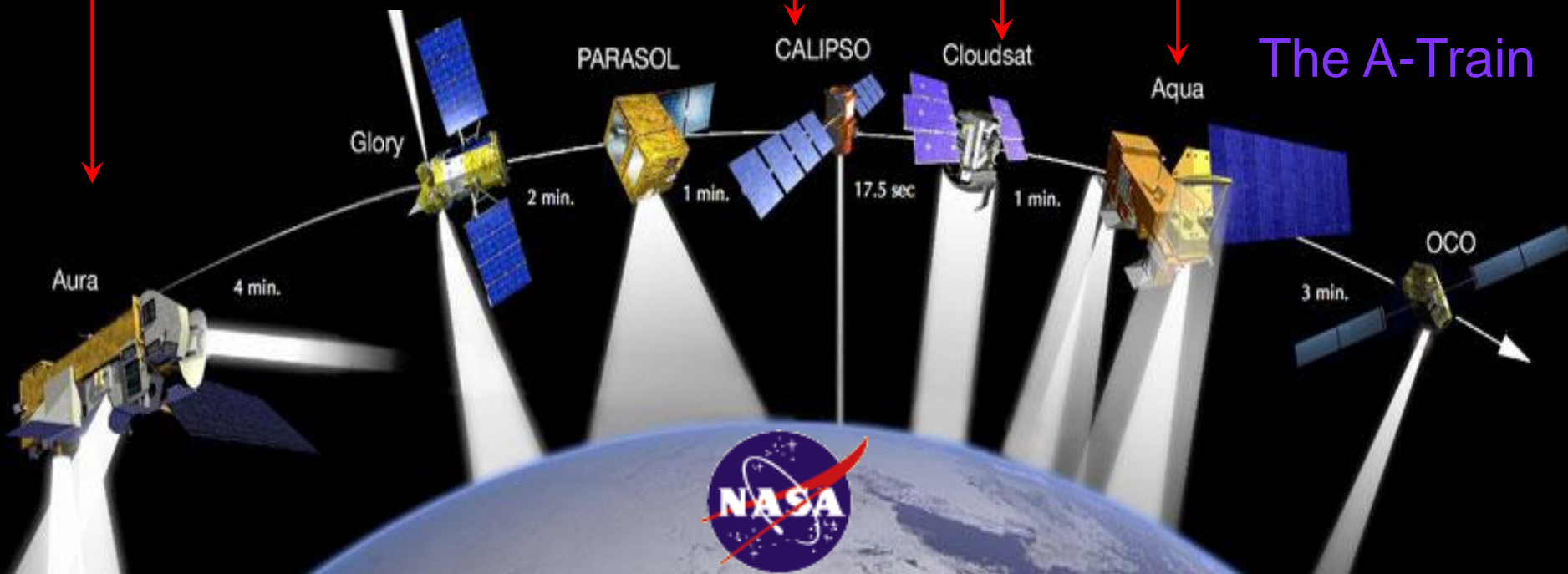
AIRS - SO_2 , ash, sulfate, ice, SO_2 profile

CloudSat

CPR - precipitation, hydrometeors

CALIPSO

CALIOP - aerosol altitude, phase/type



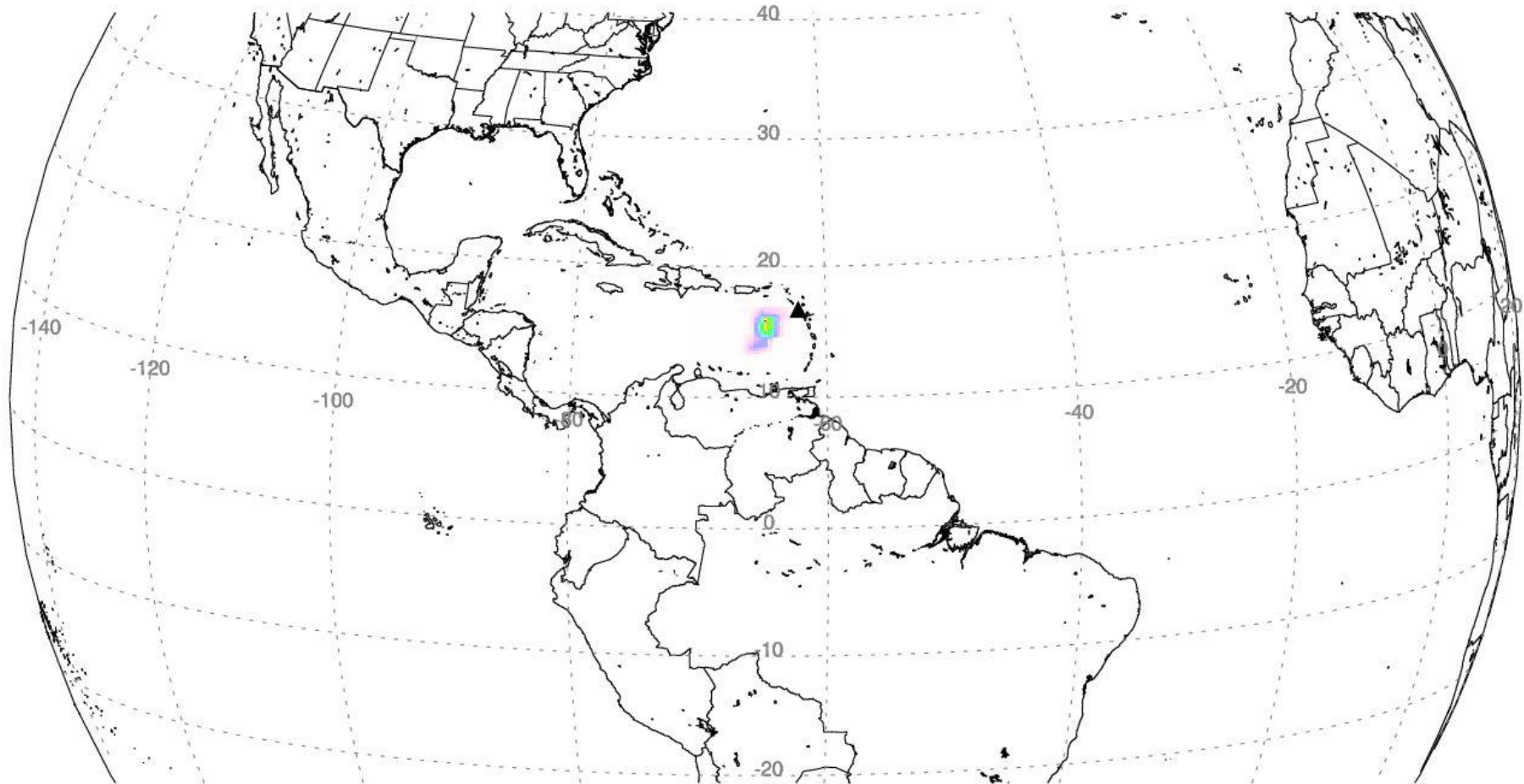
The A-Train

Soufrière Hills volcano (Montserrat) eruption, May 2006

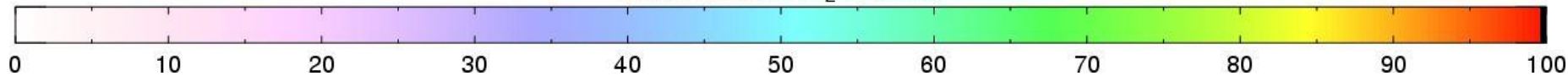
Aura/OMI - 05/20/2006 17:00-18:41 UT

Mass: 135.133 kt; Area: 202457 km²; SO₂ max: 146.85 DU at lon: -64.79 lat: 15.72

~0.2 Tg SO₂



Normalised SO₂ column



[Carn et al., 2007; Prata et al., 2007]

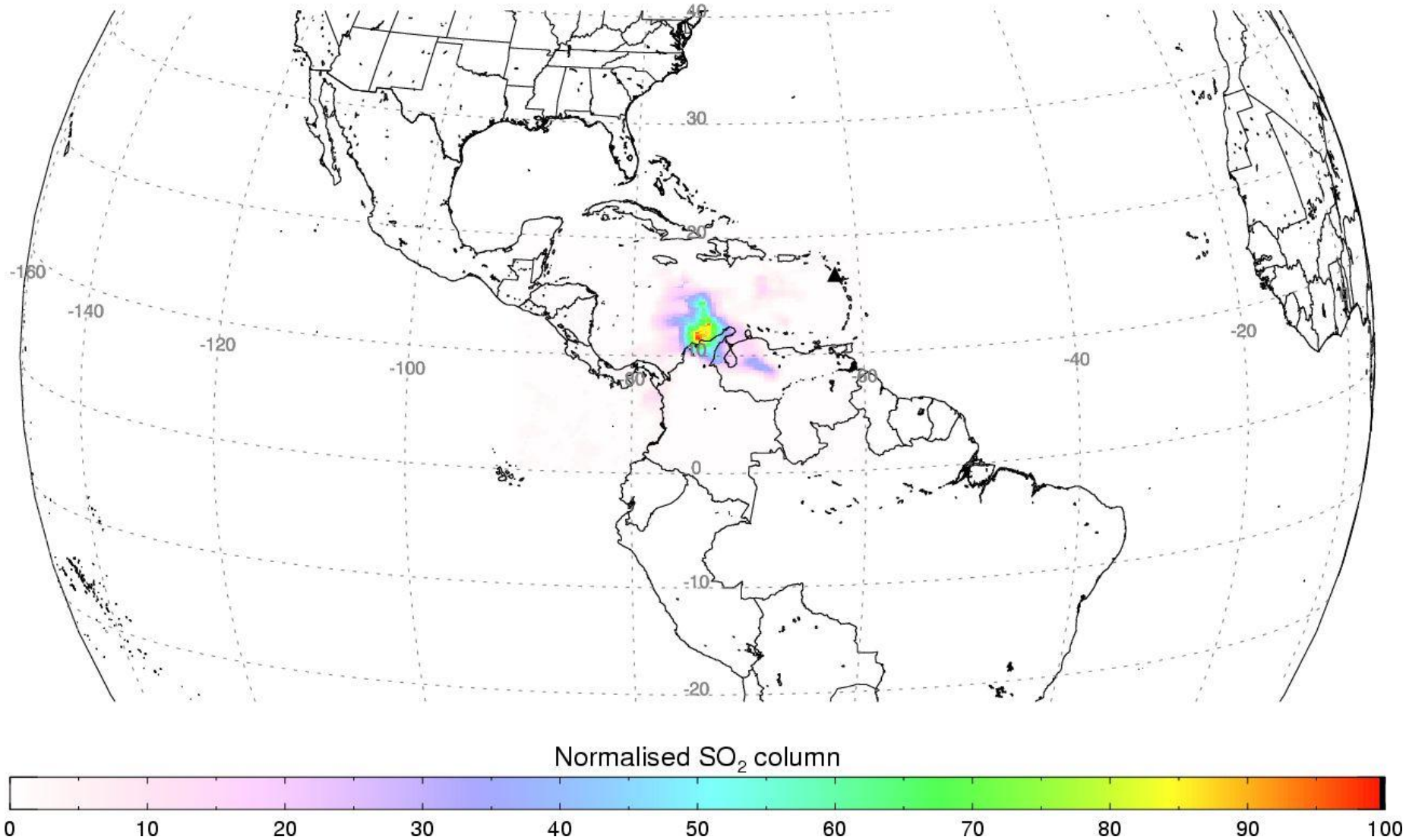
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/21/2006 17:40-19:25 UT

Mass: 195.725 kt; Area: 1400753 km²; SO₂ max: 32.71 DU at lon: -74.40 lat: 11.42

Contact: Simon Carn (scarn@umbc.edu)

NASA/KNMI/NIVR/FMI



[Carn et al., 2007; Prata et al., 2007]

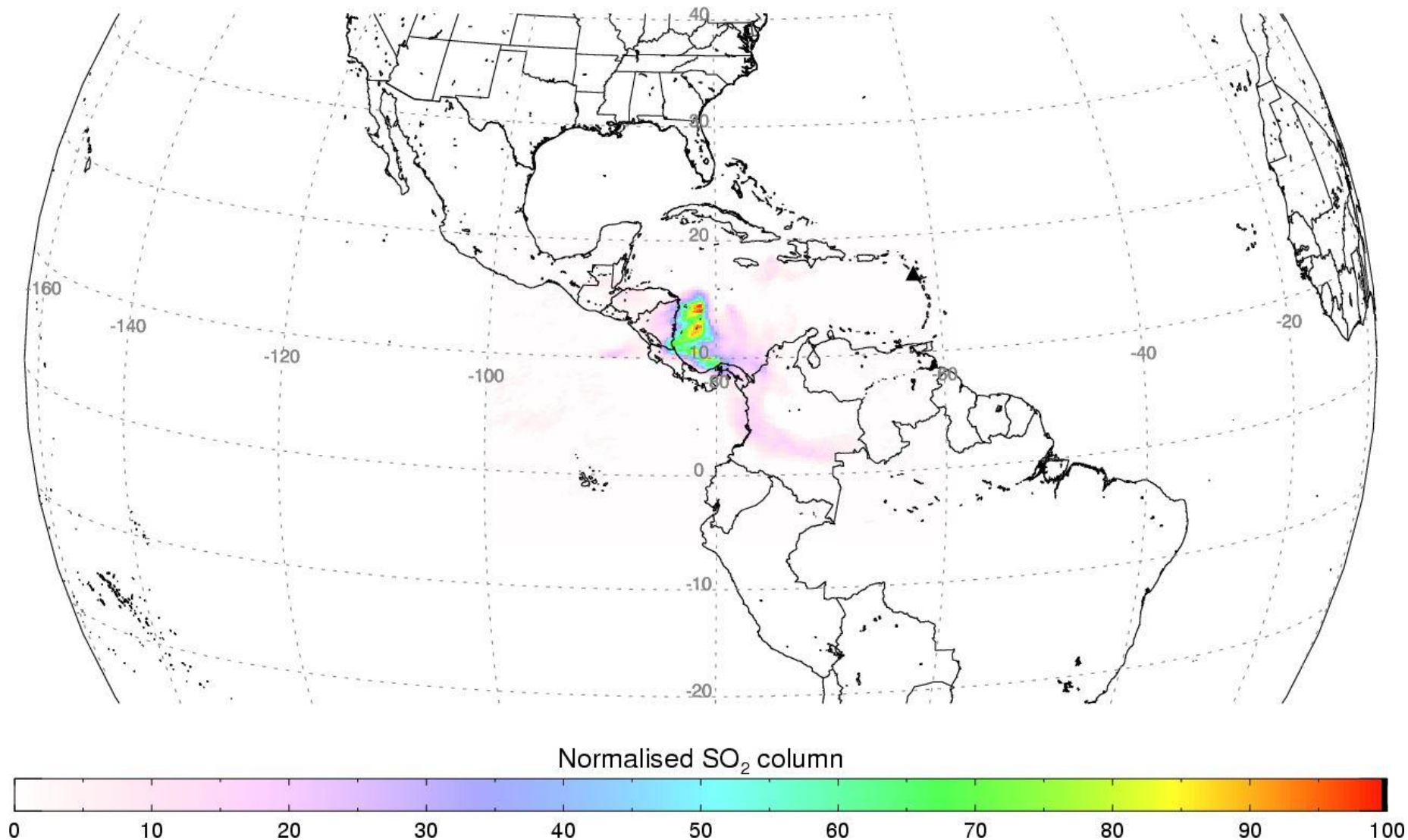
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/22/2006 16:48-20:08 UT

Mass: 188.536 kt; Area: 1880299 km²; SO₂ max: 23.66 DU at lon: -81.33 lat: 14.47

Contact: Simon Carn (scarn@umbc.edu)

NASA/KNMI/NIVR/FMI

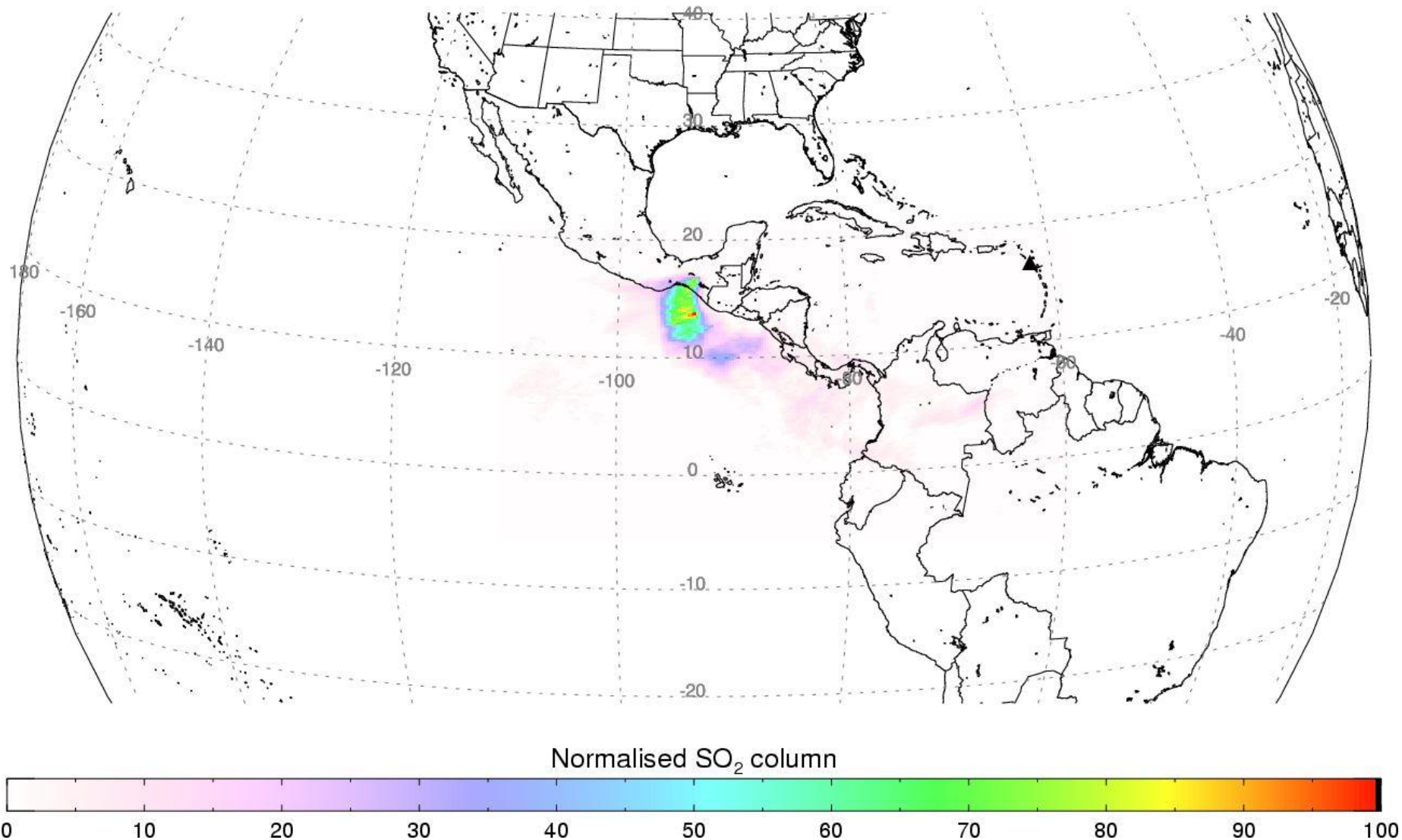


[Carn et al., 2007; Prata et al., 2007]

Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/23/2006 17:27-20:51 UT

Mass: 171.187 kt; Area: 2410030 km²; SO₂ max: 19.89 DU at lon: -93.38 lat: 13.66

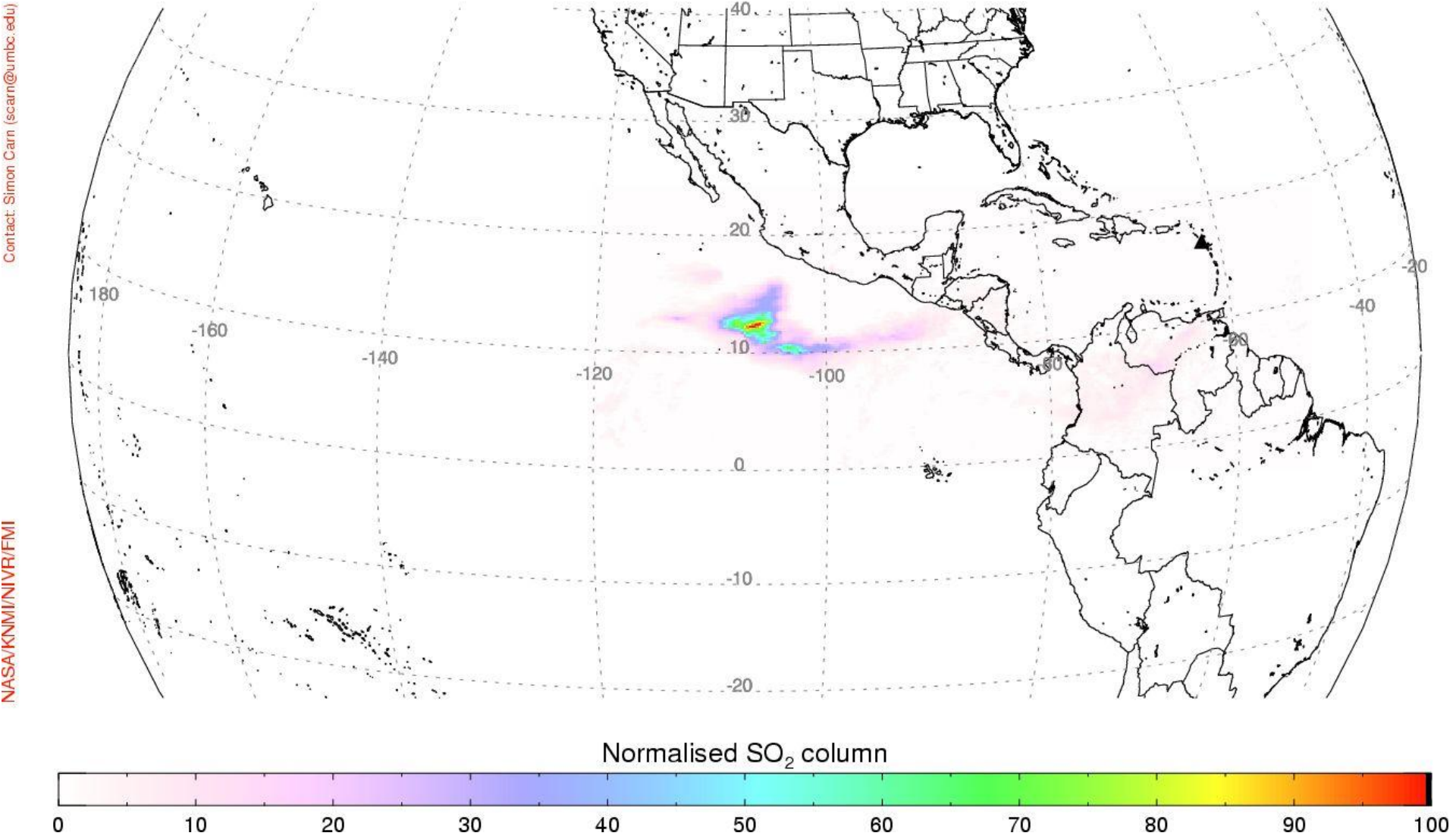


[Carn et al., 2007; Prata et al., 2007]

Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/24/2006 16:33-21:35 UT

Mass: 159.341 kt; Area: 2532097 km²; SO₂ max: 20.18 DU at lon: -107.02 lat: 12.14

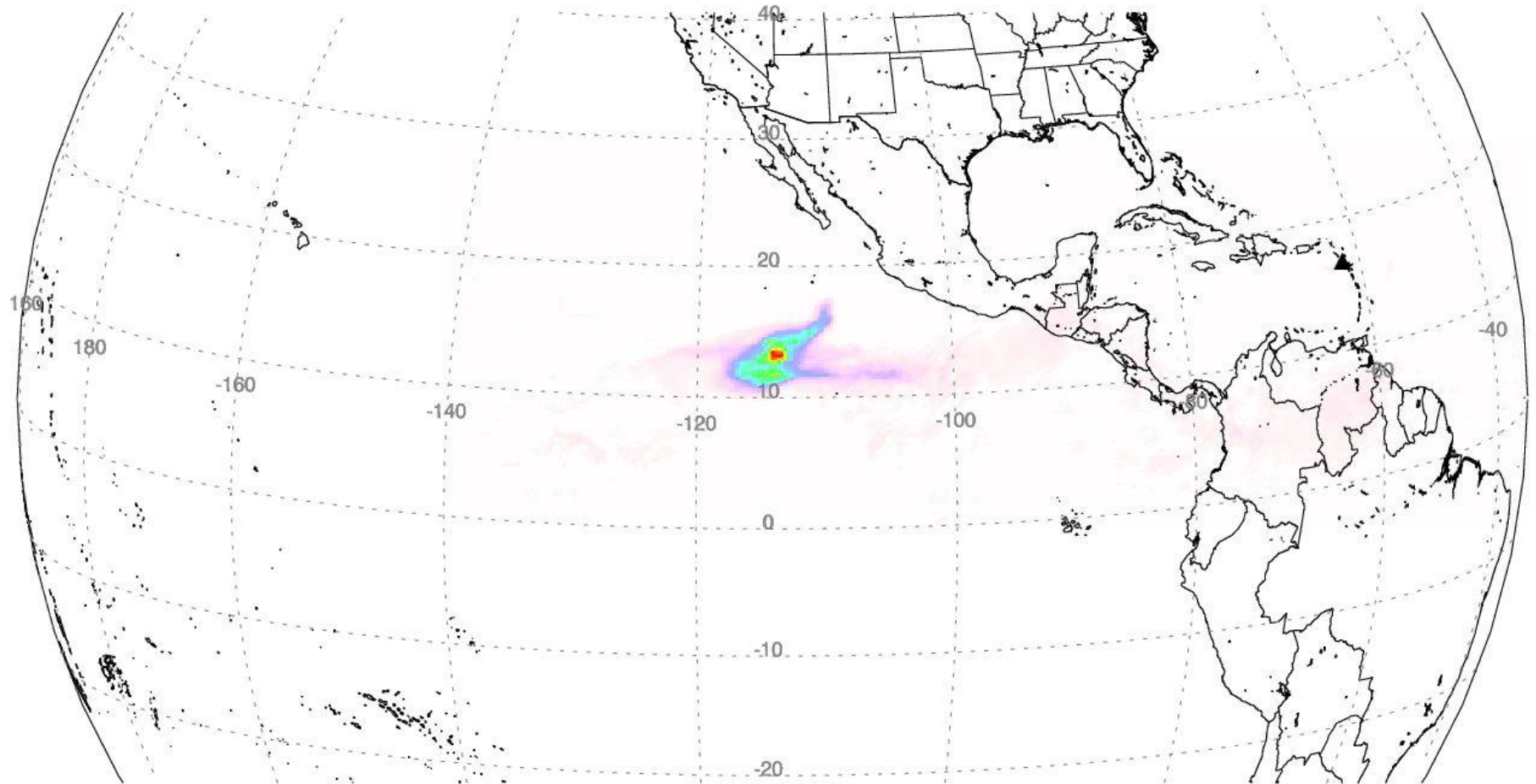


[Carn et al., 2007; Prata et al., 2007]

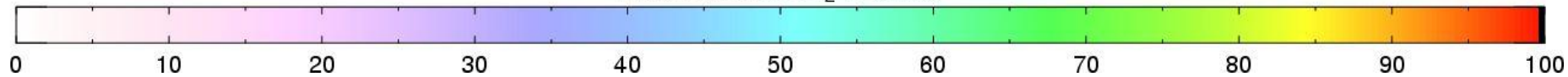
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/25/2006 14:03-22:18 UT

Mass: 168.052 kt; Area: 3126612 km²; SO₂ max: 18.41 DU at lon: -114.18 lat: 13.47



Normalised SO₂ column

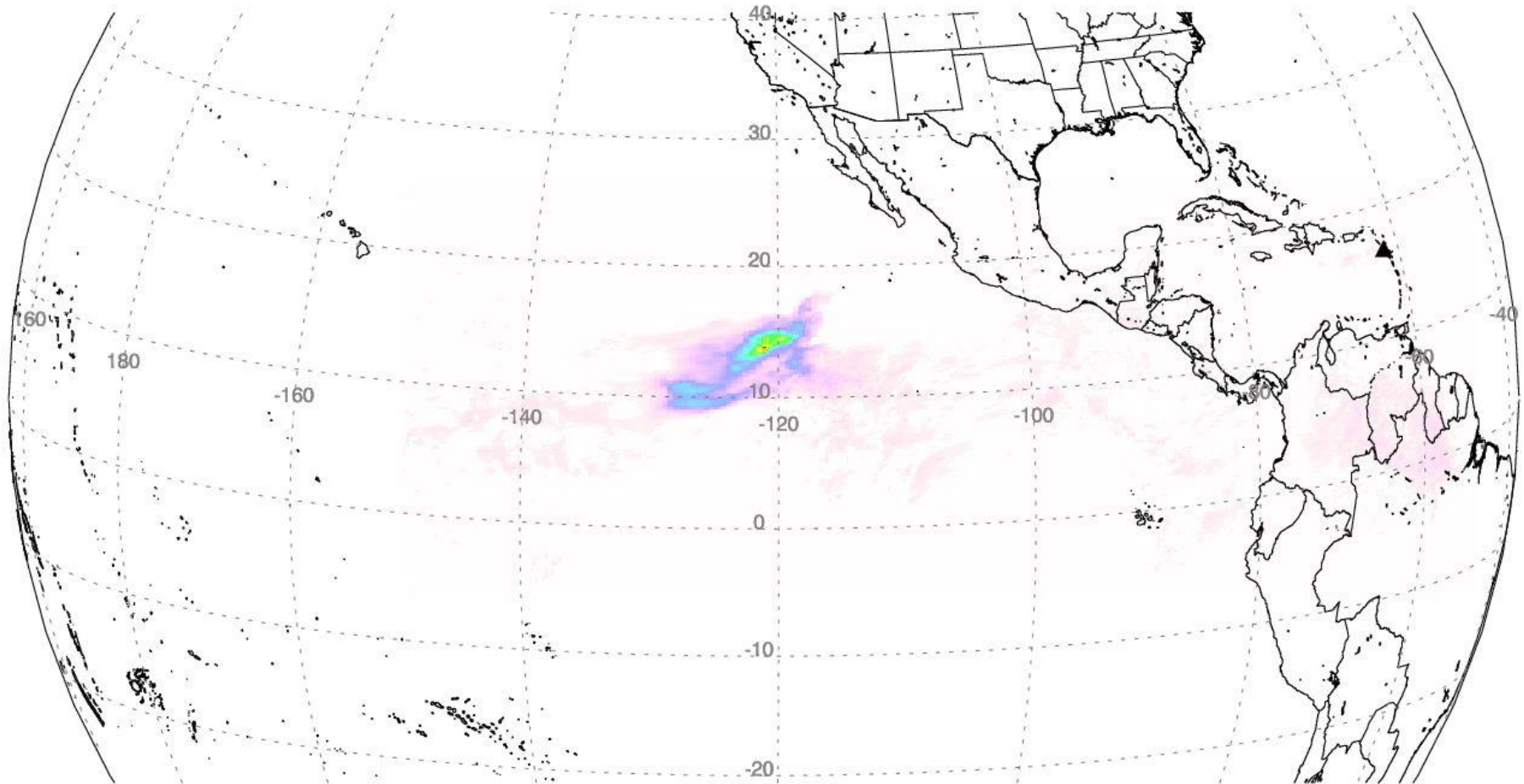


[Carn et al., 2007; Prata et al., 2007]

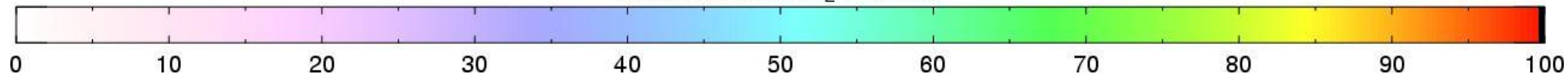
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/26/2006 16:19-23:02 UT

Mass: 146.936 kt; Area: 3468046 km²; SO₂ max: 12.14 DU at lon: -121.13 lat: 13.78



Normalised SO₂ column

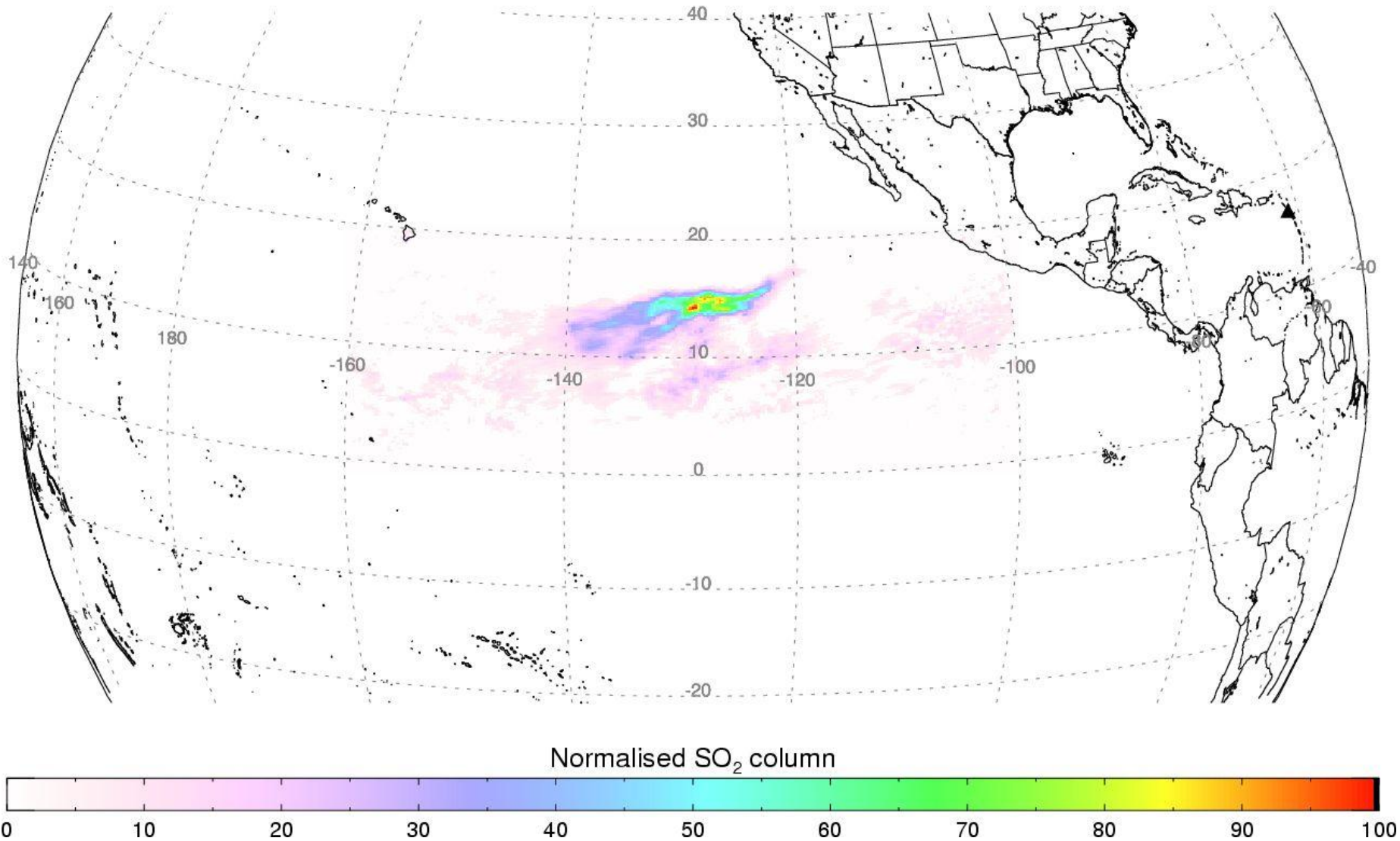


[Carn et al., 2007; Prata et al., 2007]

Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/27/2006 20:21-23:45 UT

Mass: 110.209 kt; Area: 2575001 km²; SO₂ max: 8.59 DU at lon: -128.96 lat: 14.21

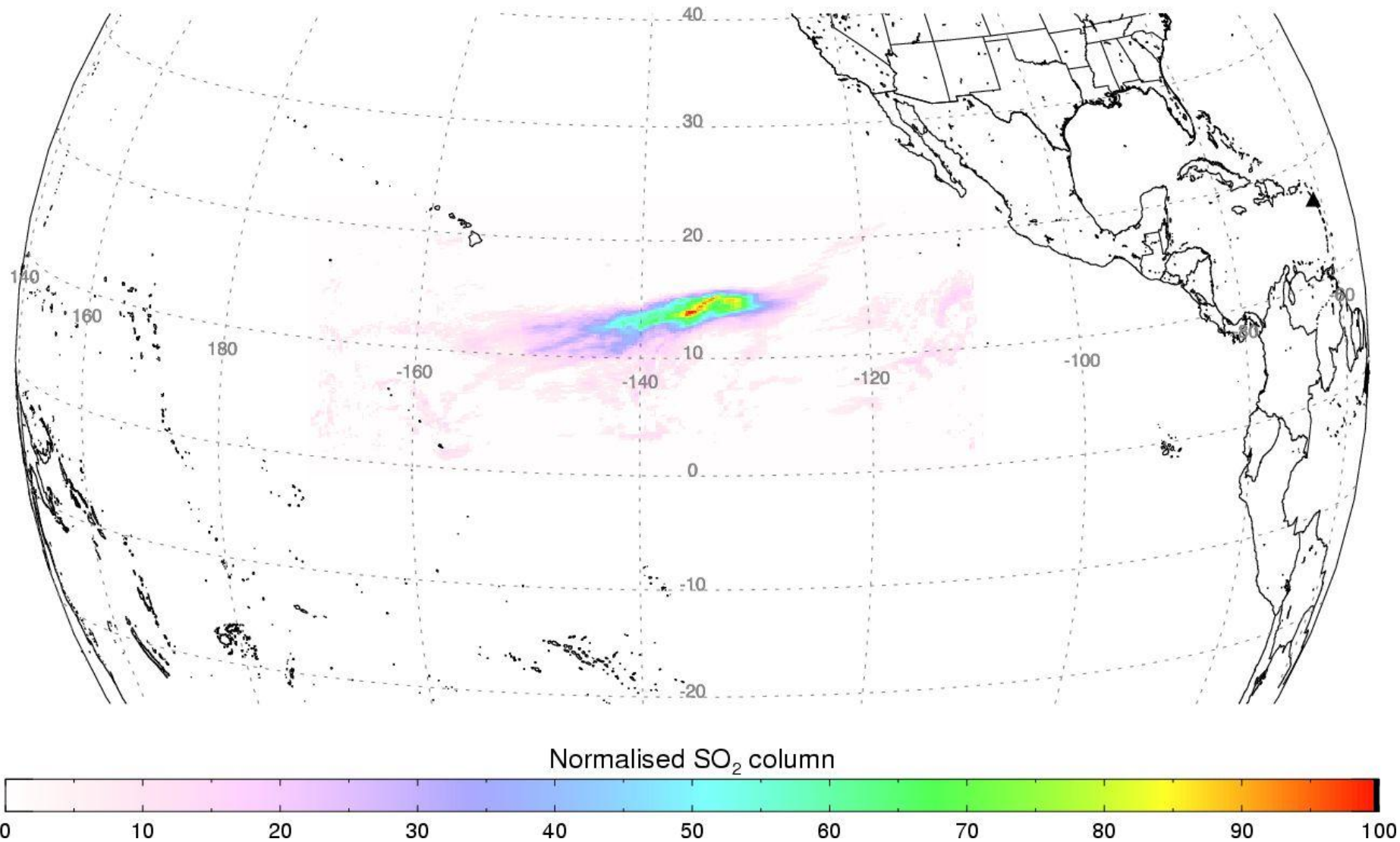


[Carn et al., 2007; Prata et al., 2007]

Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/28/2006 00:22-22:50 UT

Mass: 108.896 kt; Area: 2279174 km²; SO₂ max: 8.11 DU at lon: -135.54 lat: 13.82



[Carn et al., 2007; Prata et al., 2007]

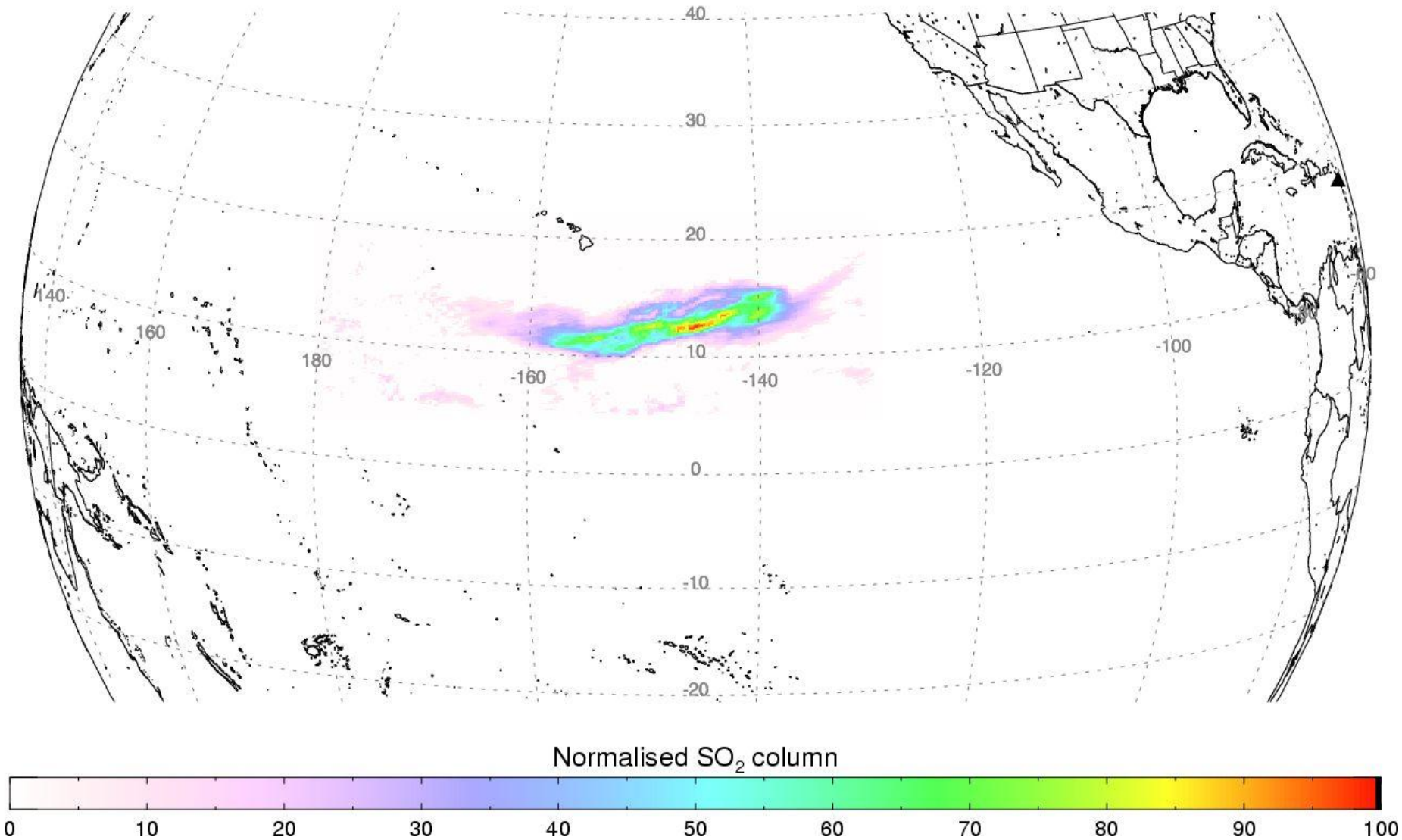
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/29/2006 01:07-23:33 UT

Mass: 98.493 kt; Area: 1701411 km²; SO₂ max: 6.22 DU at lon: -145.52 lat: 12.46

Contact: Simon Carn (scarn@umbc.edu)

NASA/KNMI/NIVR/FMI



[Carn et al., 2007; Prata et al., 2007]

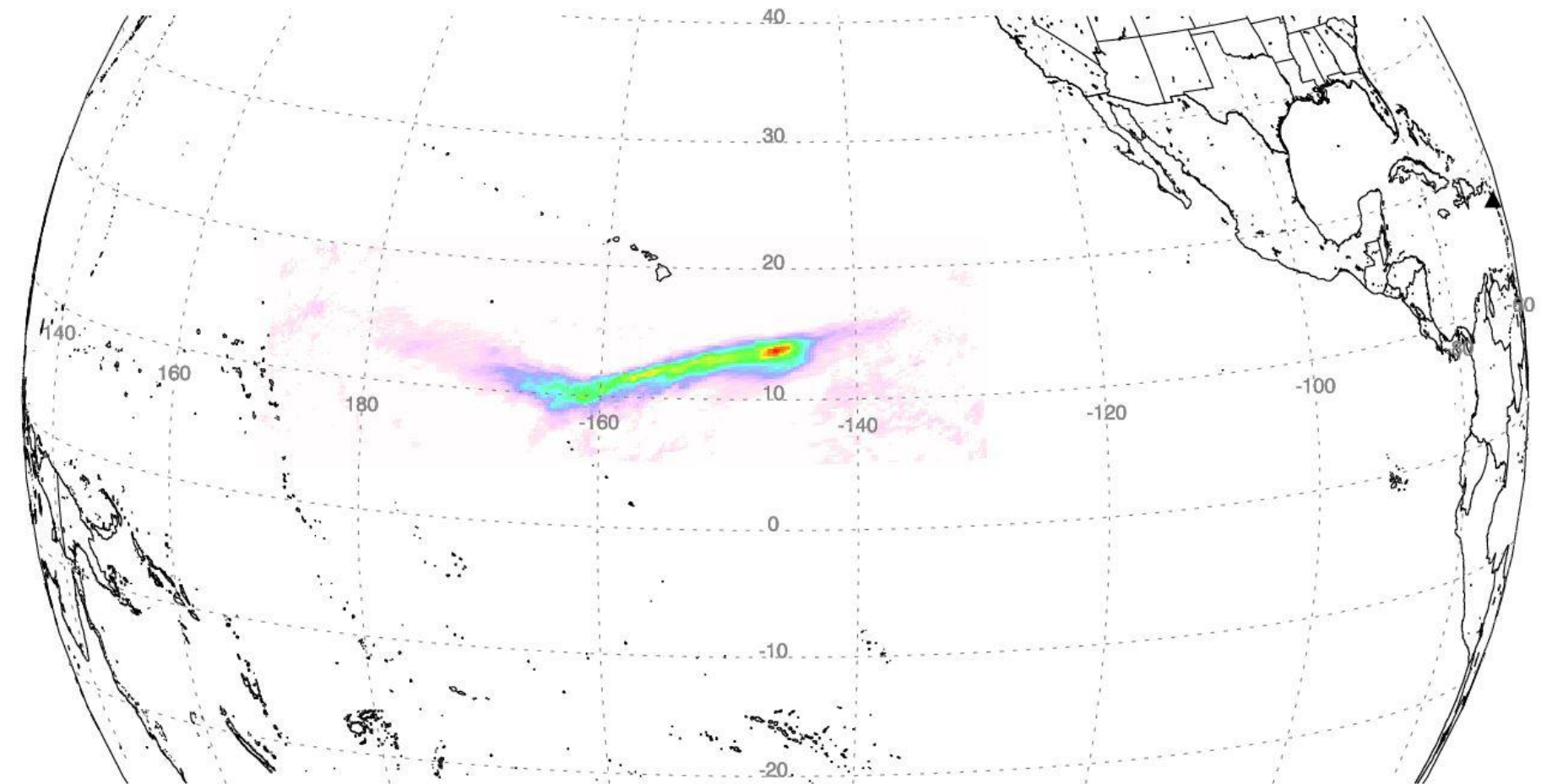
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/30/2006 00:11-22:37 UT

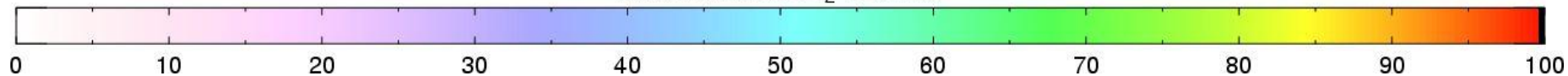
Mass: 107.076 kt; Area: 2034725 km²; SO₂ max: 6.74 DU at lon: -146.34 lat: 13.83

Contact: Simon Carn (scarn@umbc.edu)

NASA/KNMI/NIVR/FMI



Normalised SO₂ column



[Carn et al., 2007; Prata et al., 2007]

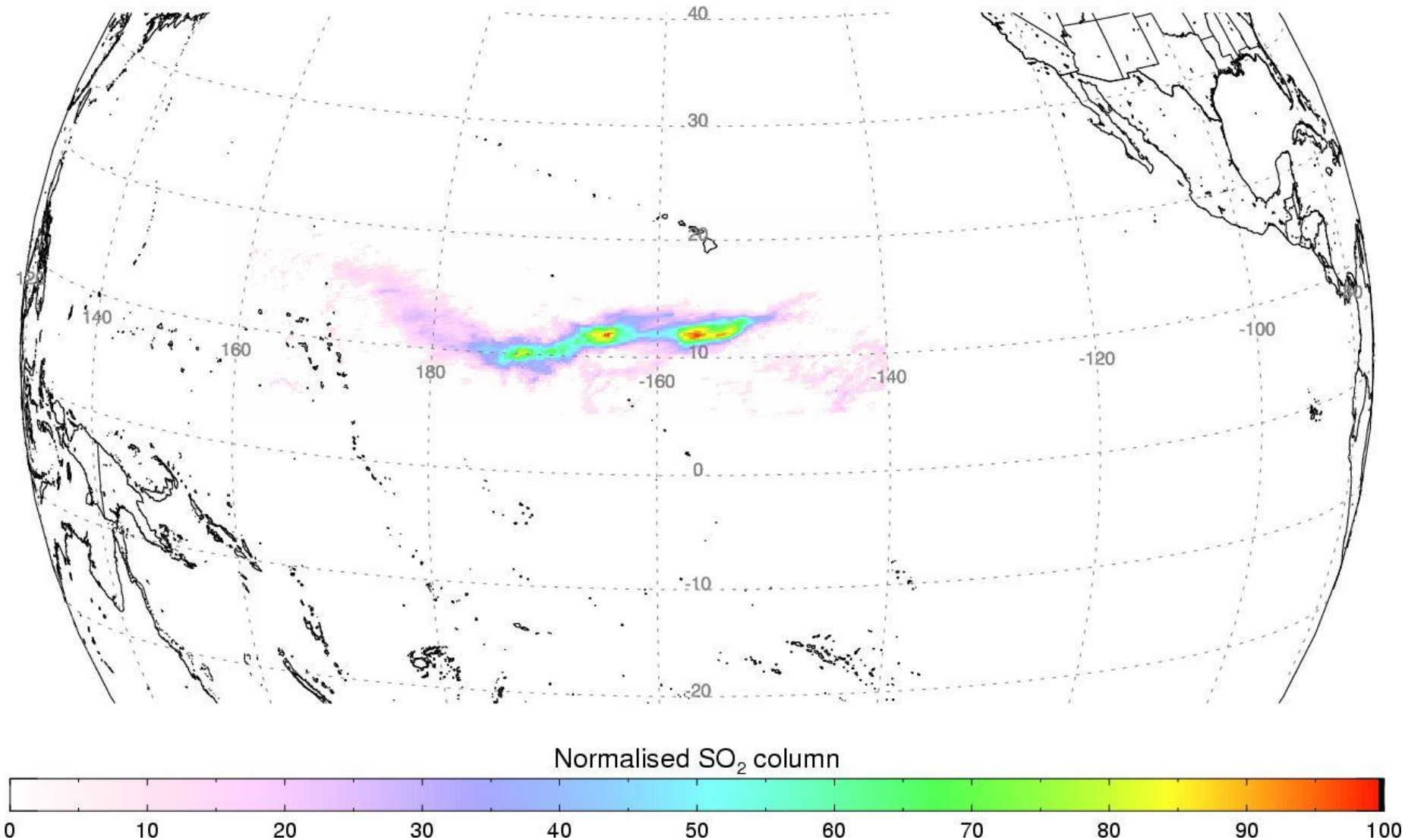
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/31/2006 00:54-23:21 UT

Mass: 96.573 kt; Area: 2063998 km²; SO₂ max: 6.10 DU at lon: -156.59 lat: 11.76

Contact: Simon Carn (scarn@umbc.edu)

NASA/KNMI/NIVR/FMI

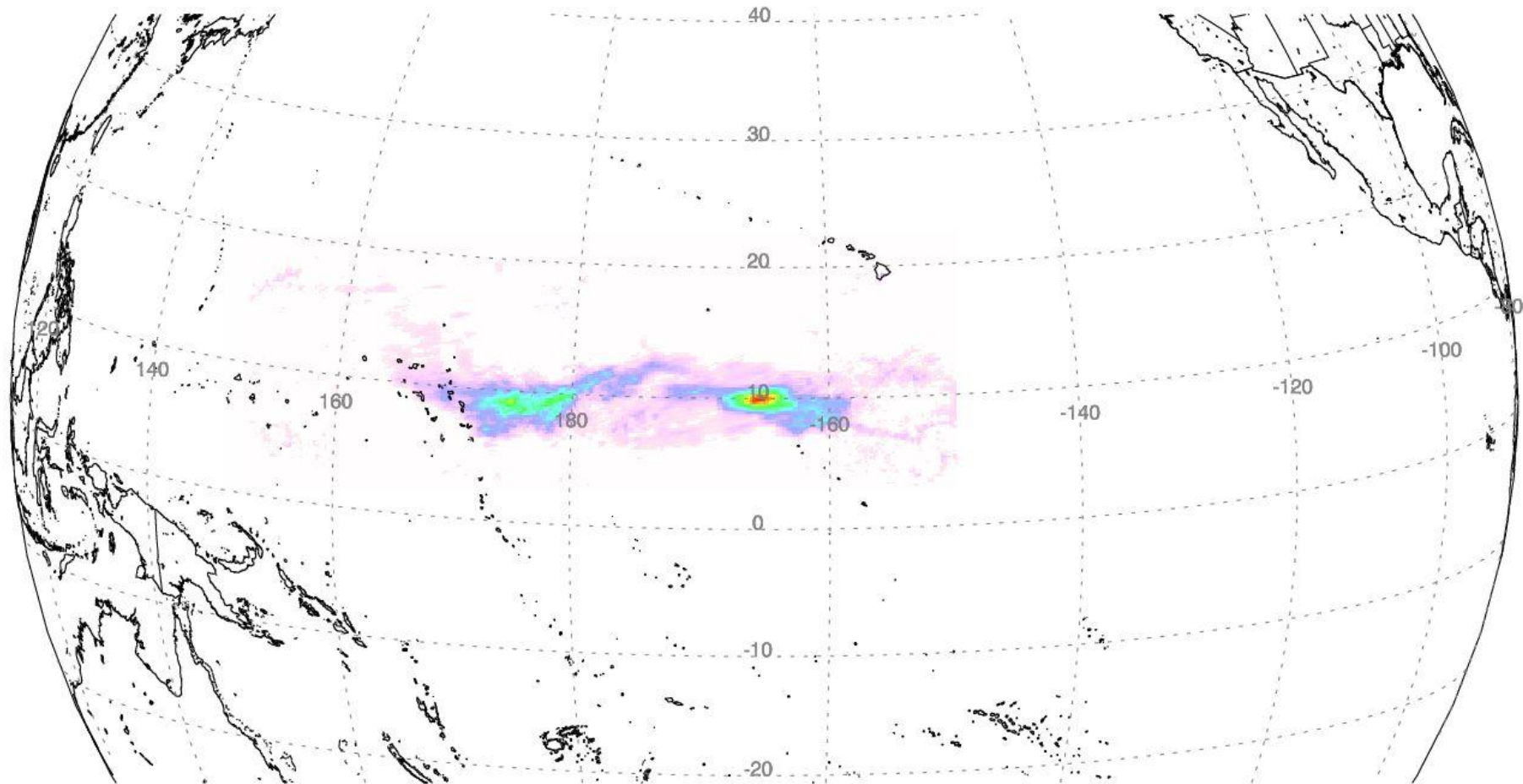


[Carn et al., 2007; Prata et al., 2007]

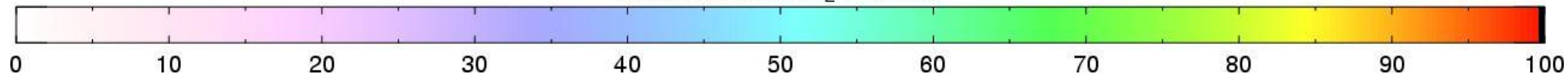
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/02/2006 00:00-24:00 UT

Mass: 92.692 kt; Area: 2247222 km²; SO₂ max: 5.54 DU at lon: -165.01 lat: 9.94



Normalised SO₂ column



[Carn et al., 2007; Prata et al., 2007]

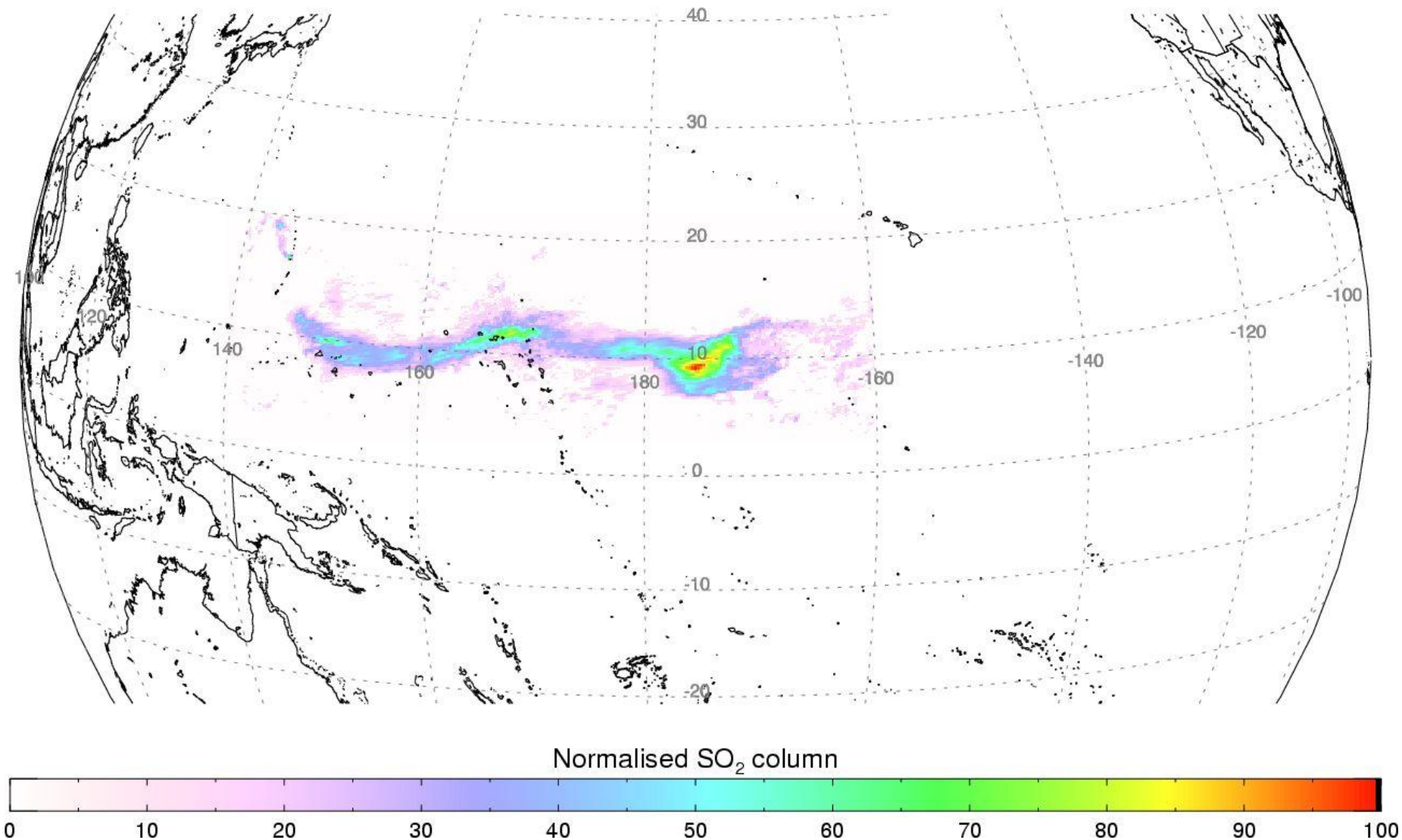
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/03/2006 00:41-04:04 UT

Mass: 82.835 kt; Area: 2209377 km²; SO₂ max: 3.85 DU at lon: -175.63 lat: 9.17

Contact: Simon Carn (scarn@umbc.edu)

NASA/KNMI/NIVR/FMI



[Carn et al., 2007; Prata et al., 2007]

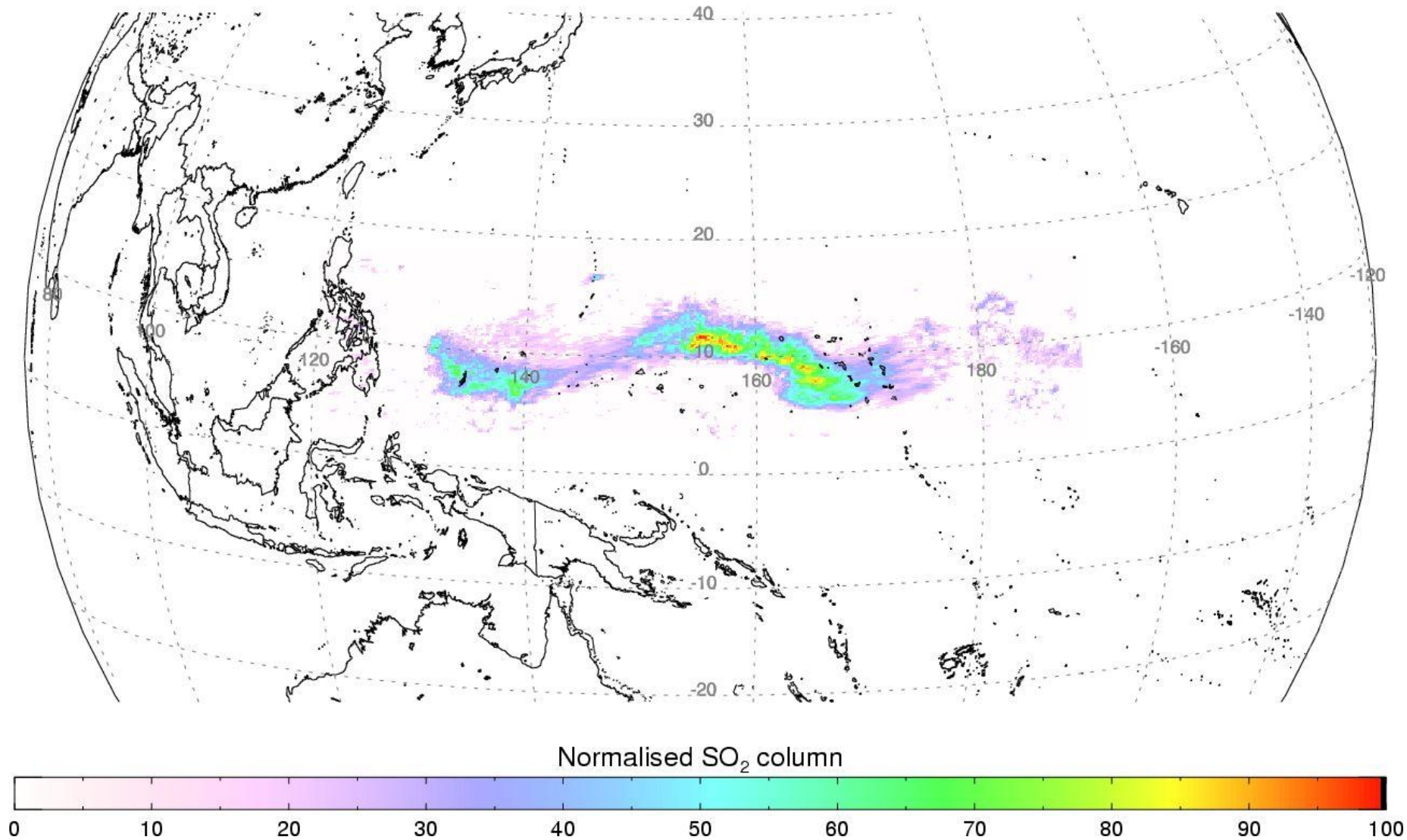
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/04/2006 01:25-06:23 UT

Mass: 79.103 kt; Area: 2352265 km²; SO₂ max: 3.01 DU at lon: 155.20 lat: 11.69

Contact: Simon Carn (scarn@umbc.edu)

NASA/KNMI/NIVR/FMI

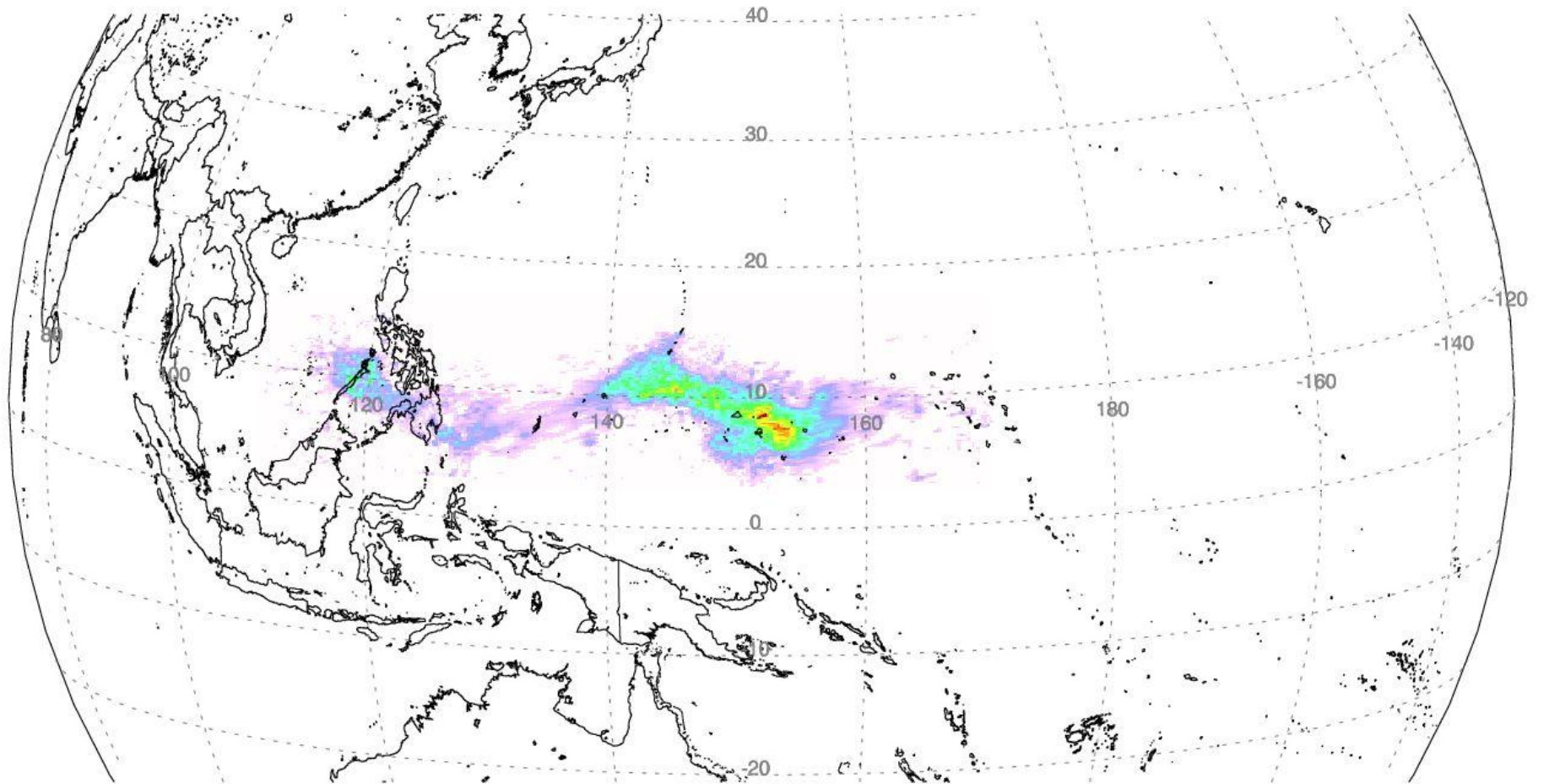


[Carn et al., 2007; Prata et al., 2007]

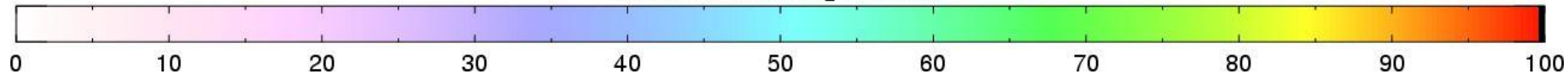
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/05/2006 02:08-07:05 UT

Mass: 71.854 kt; Area: 2170677 km²; SO₂ max: 2.94 DU at lon: 151.98 lat: 8.57



Normalised SO₂ column



[Carn et al., 2007; Prata et al., 2007]

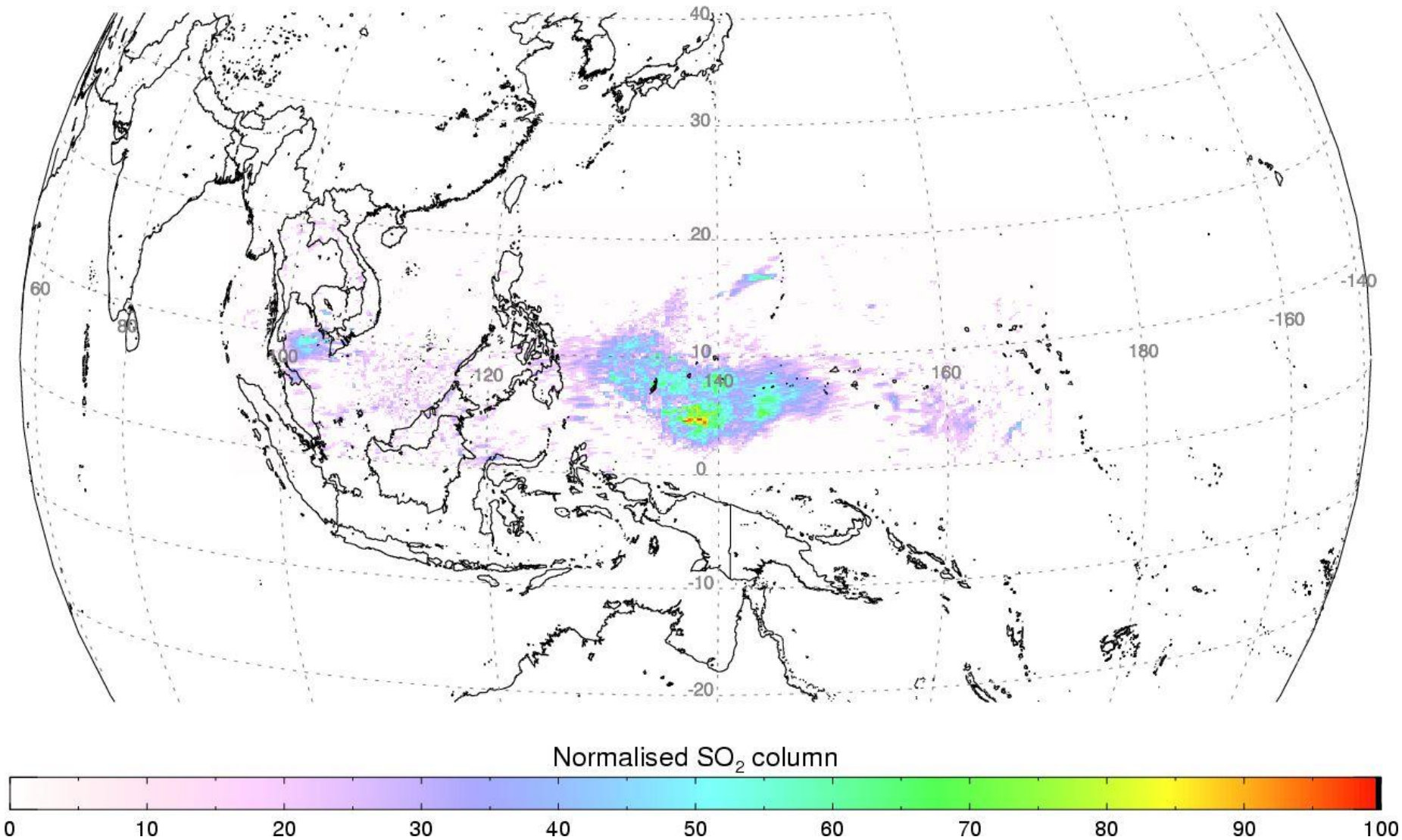
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/06/2006 02:50-07:53 UT

Mass: 54.517 kt; Area: 1986410 km²; SO₂ max: 2.67 DU at lon: 138.03 lat: 5.65

Contact: Simon Carn (scarn@umbc.edu)

NASA/KNMI/NIVR/FMI



[Carn et al., 2007; Prata et al., 2007]

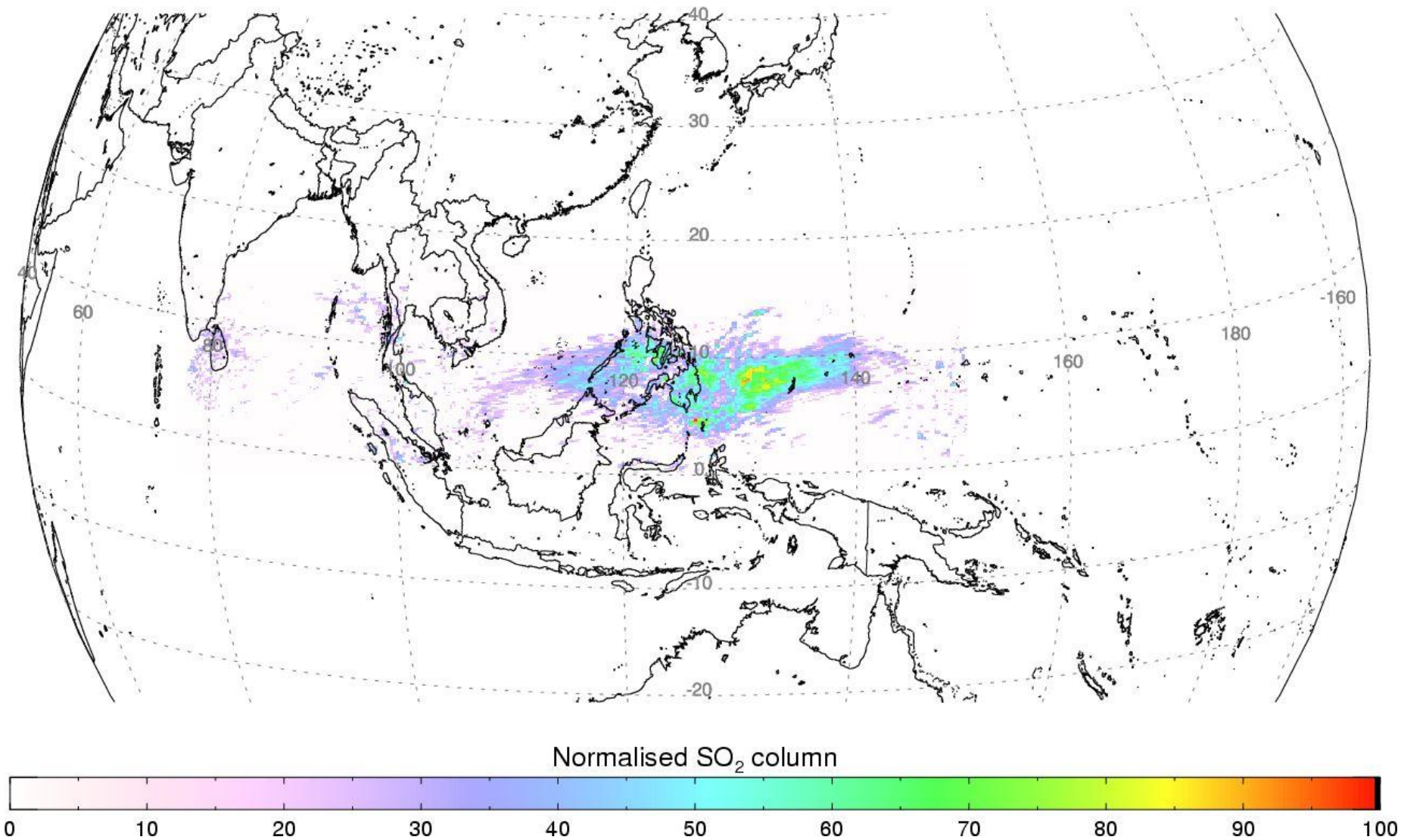
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/07/2006 03:34-08:34 UT

Mass: 45.728 kt; Area: 1734106 km²; SO₂ max: 2.12 DU at lon: 126.13 lat: 4.70

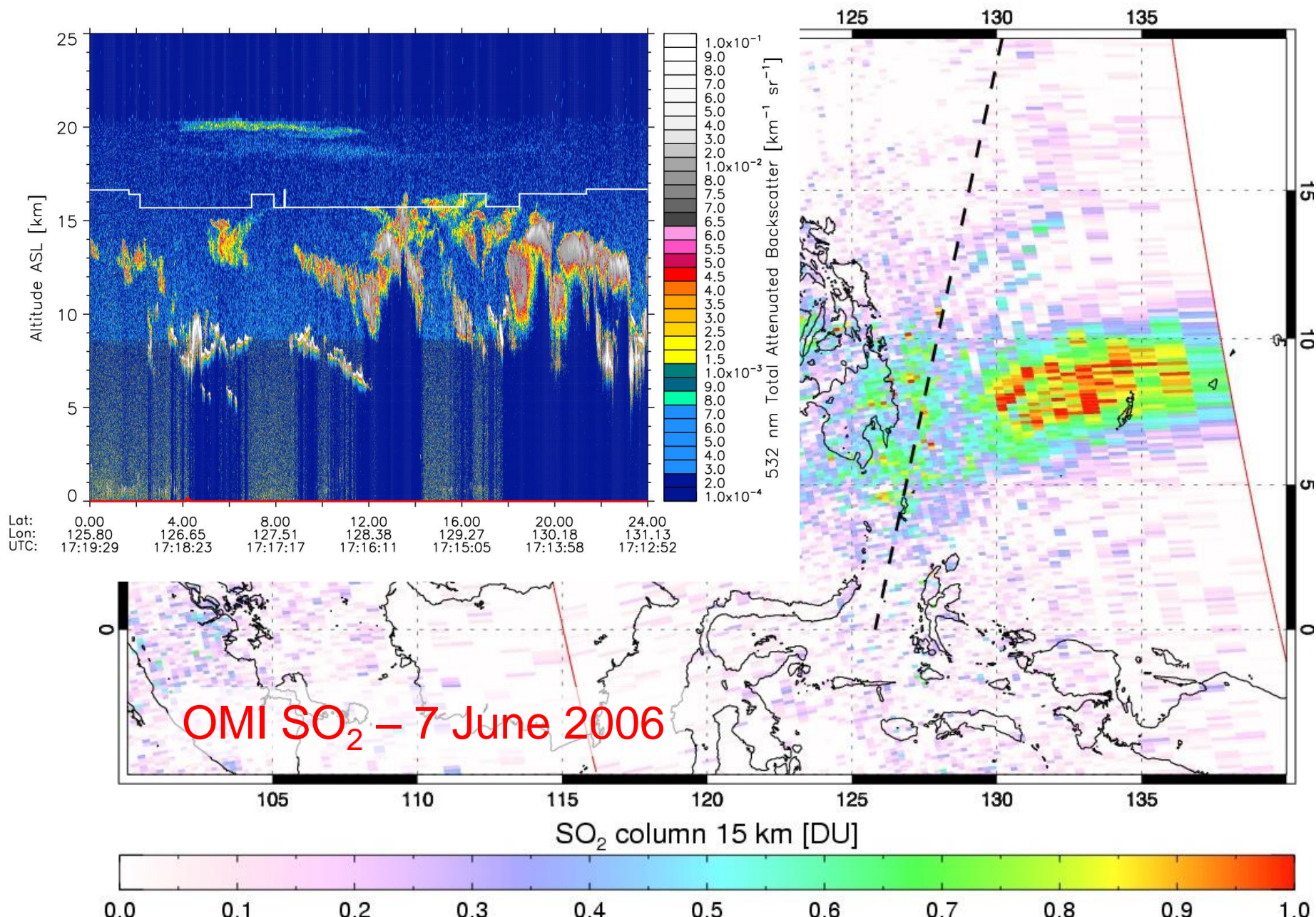
Contact: Simon Carn (scarn@umbc.edu)

NASA/KNMI/NIVR/FMI

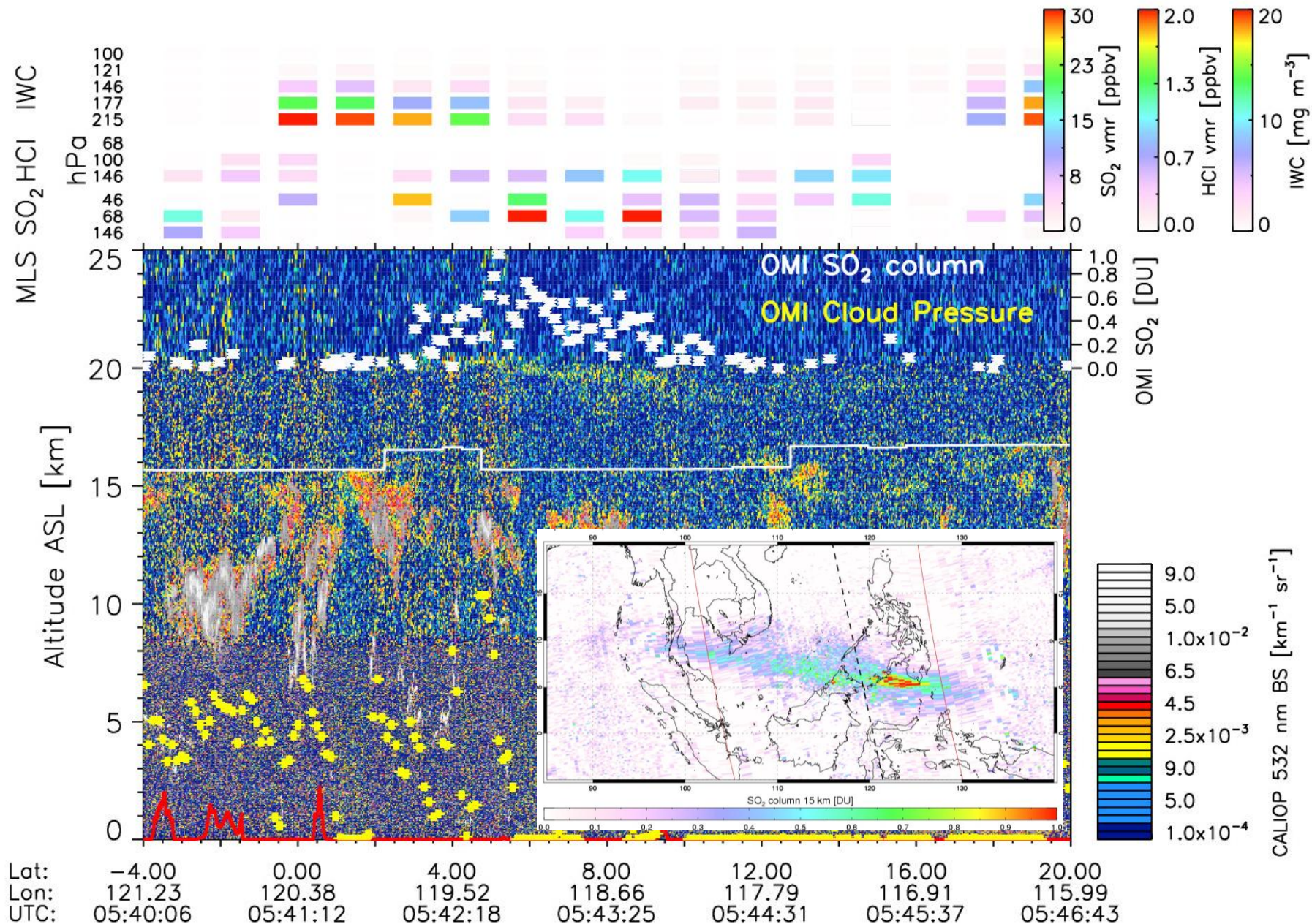


[Carn et al., 2007; Prata et al., 2007]

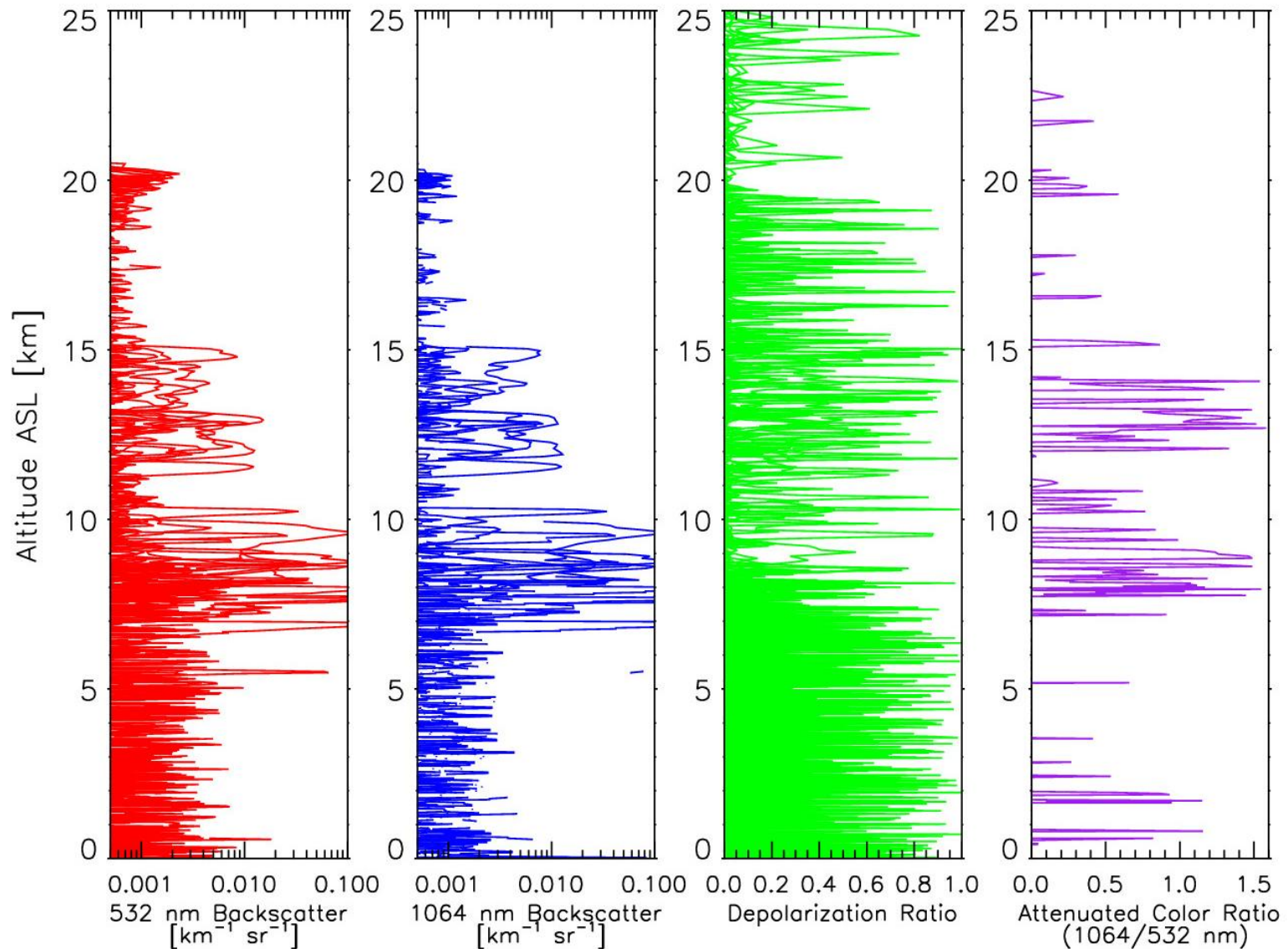
CALIPSO first light – 7 June 2006



CALIPSO – OMI – MLS: 8 June 2006

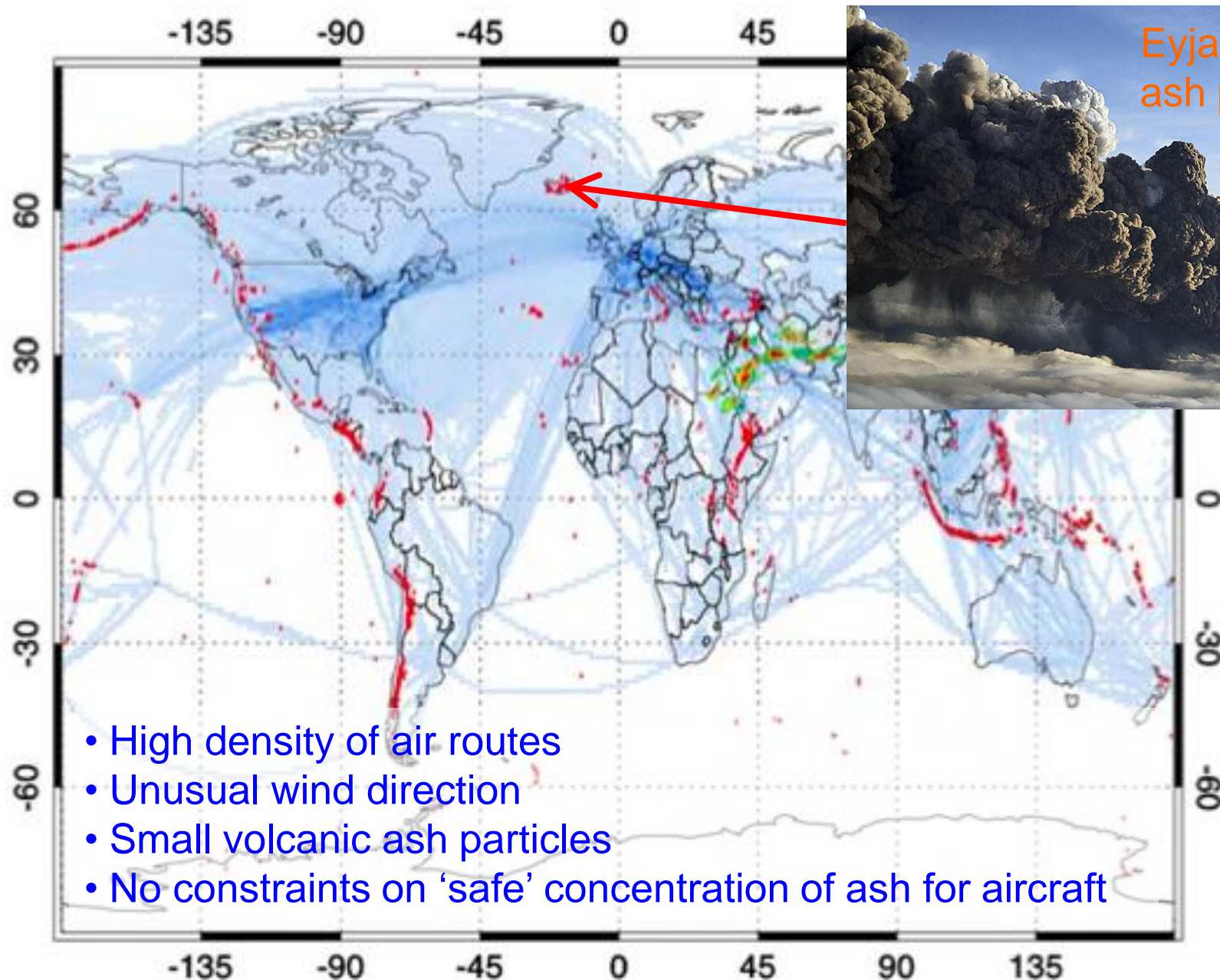


CALIPSO profiles through SHV aerosol cloud



- Aerosol layer non-depolarizing
- Liquid sulfate aerosol dominant

The 2010 eruption of Eyjafjallajökull (Iceland)

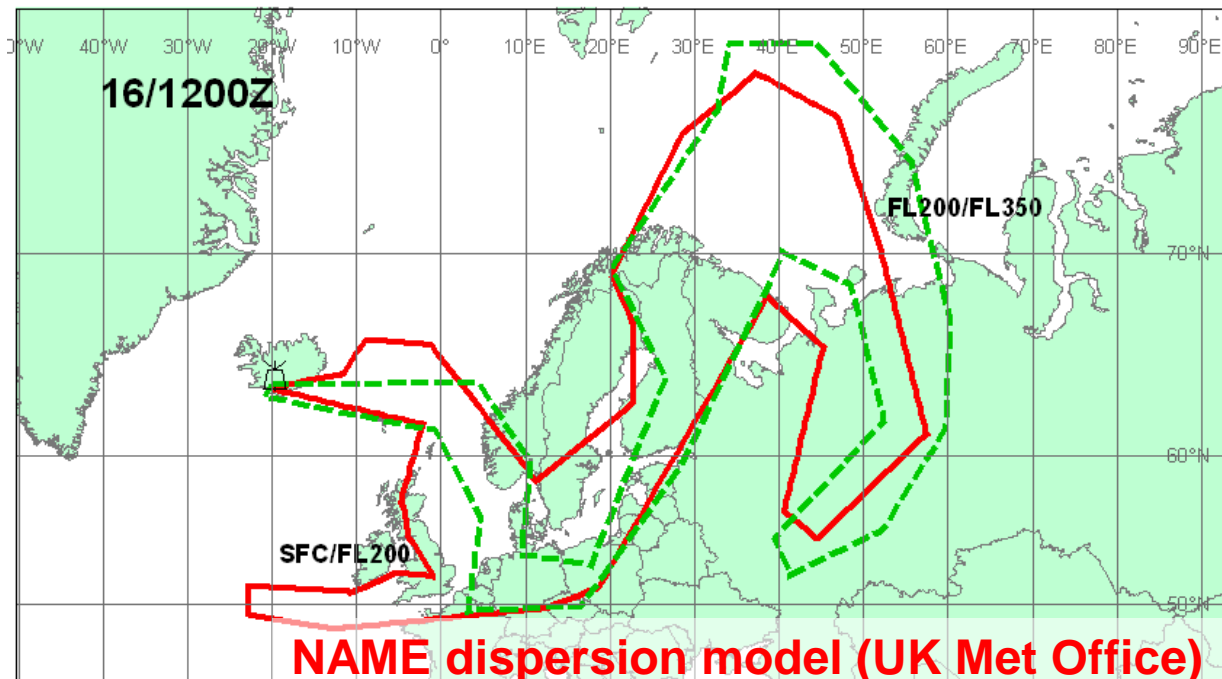
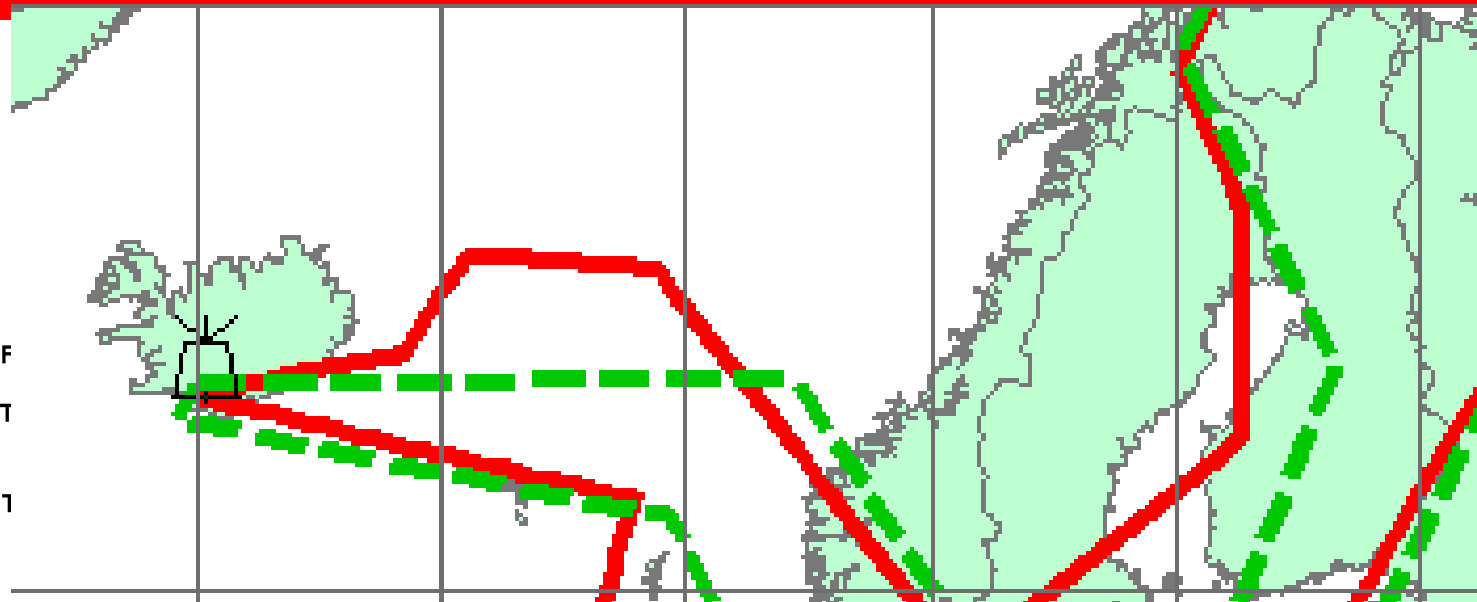


Volcanic Ash Advisory (VAA) and OMI AI – April 16

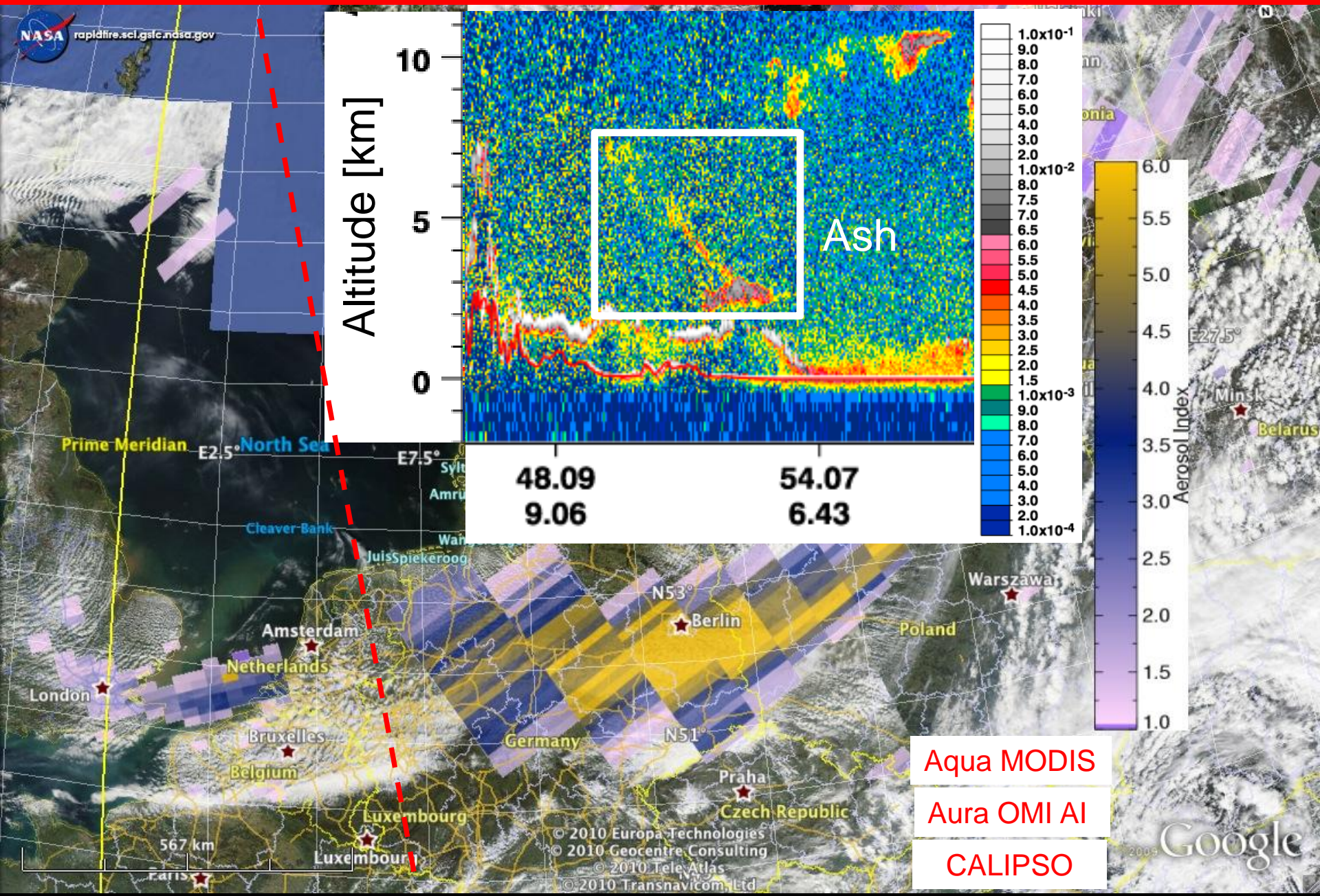
VA ADVISORY
DTG: 20100416/0600Z
VAAC: LONDON
VOLCANO:
EYJAFJALLAJOKULL
PSN: N6338 W01937
AREA: ICELAND

SUMMIT ELEV: 1666M
ADVISORY NR: 2010/009
INFO SOURCE: ICELAND MET OFF
AVIATION COLOUR CODE: RED
ERUPTION DETAILS: SIGNIFICANT
CONTINUING, REACHING FL180.

RMK: ASH CONCENTRATIONS W/1
UNKNOWN. NO SIGNIFICANT ASH
NXT ADVISORY: 20100416/1200Z



A-Train measurements – April 16



Eyjafjallajökull: 'strong' and 'weak' eruption plumes



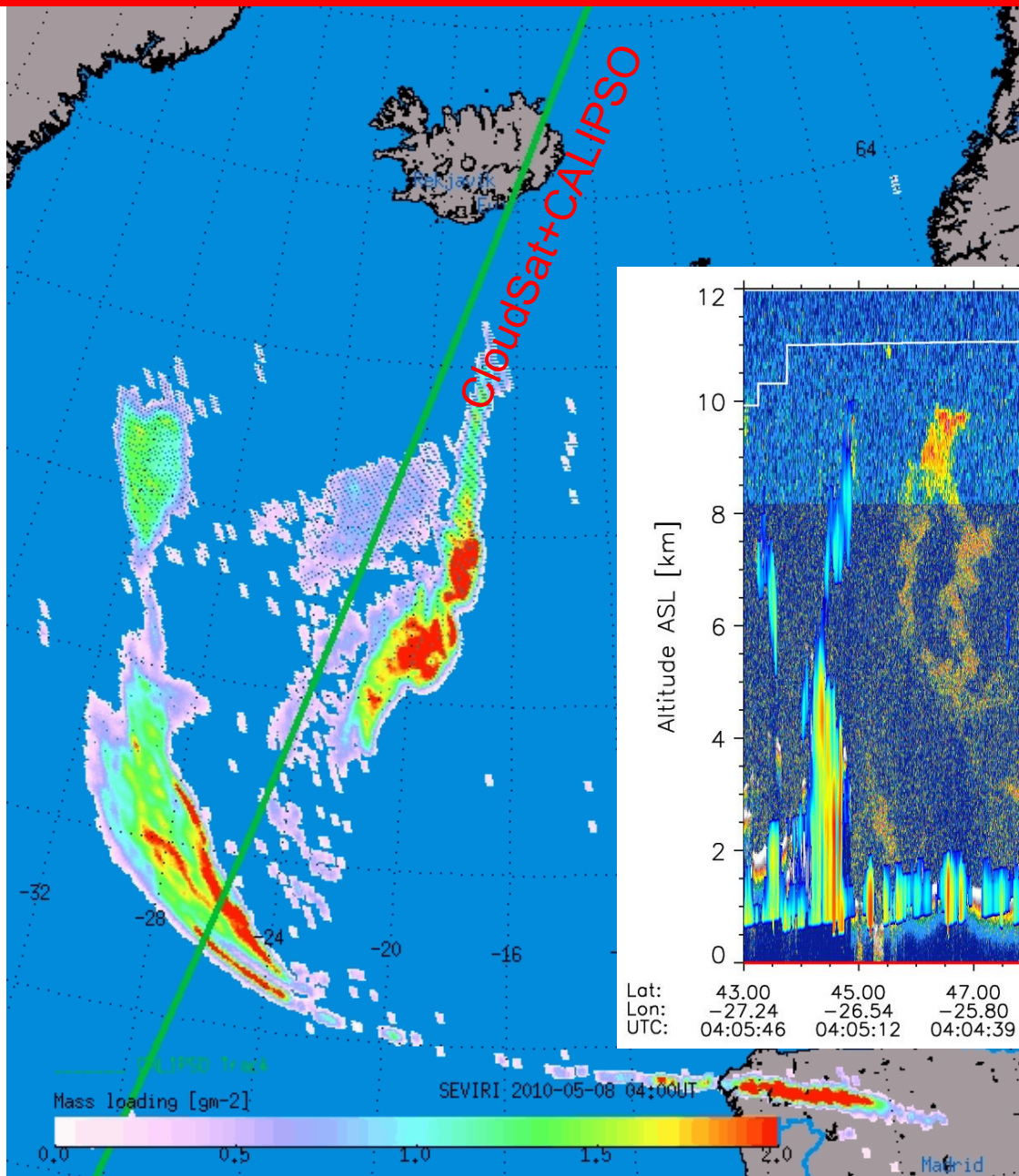
$$H = 1.67Q^{0.259}$$

- Empirical relationship of mass eruption rate (Q) to plume height (H) for '**strong**' plumes
- Assumes a single injection height
- Does not account for environmental factors (e.g., wind, humidity), gravity current intrusions etc.

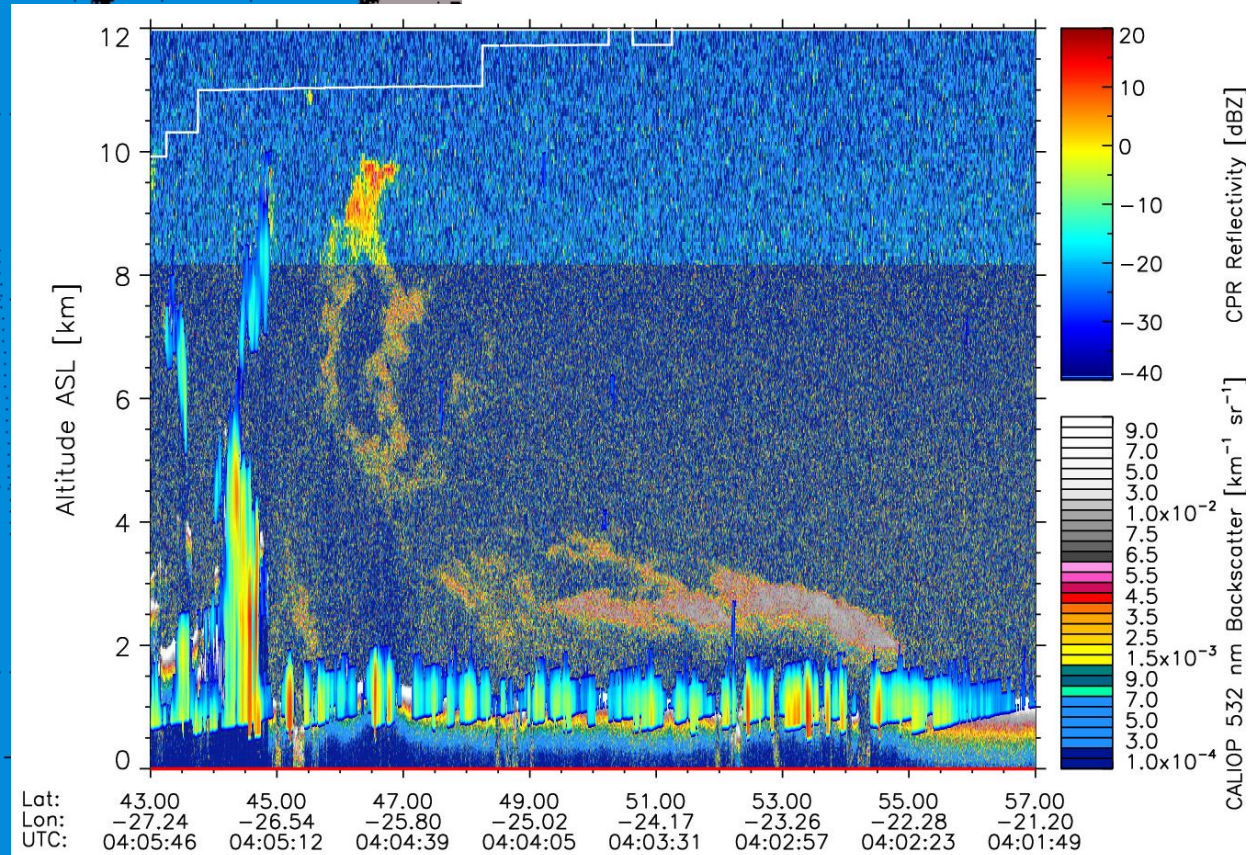


- When does advection-diffusion take over?
- -> Initialize models with accurate vertical profile information

A-Train observations of Eyjafjallajökull plume – May 8, 2010

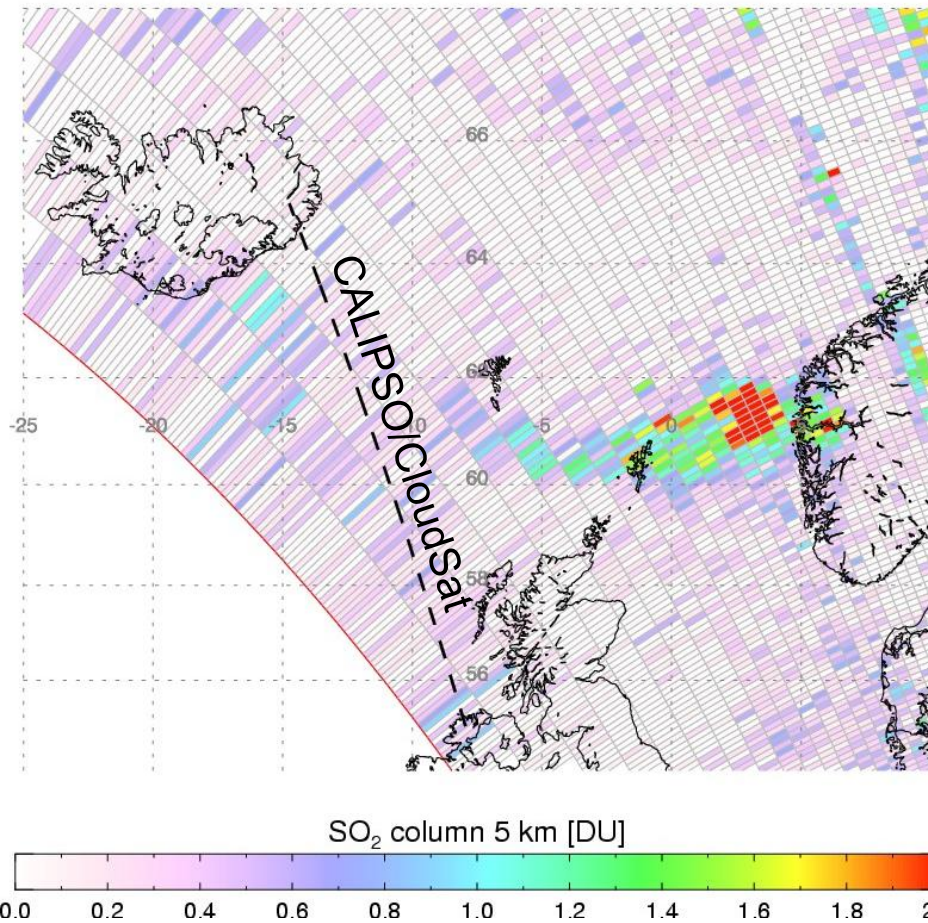


- Ash concentration = mass loading/thickness
- Thickness from CALIOP

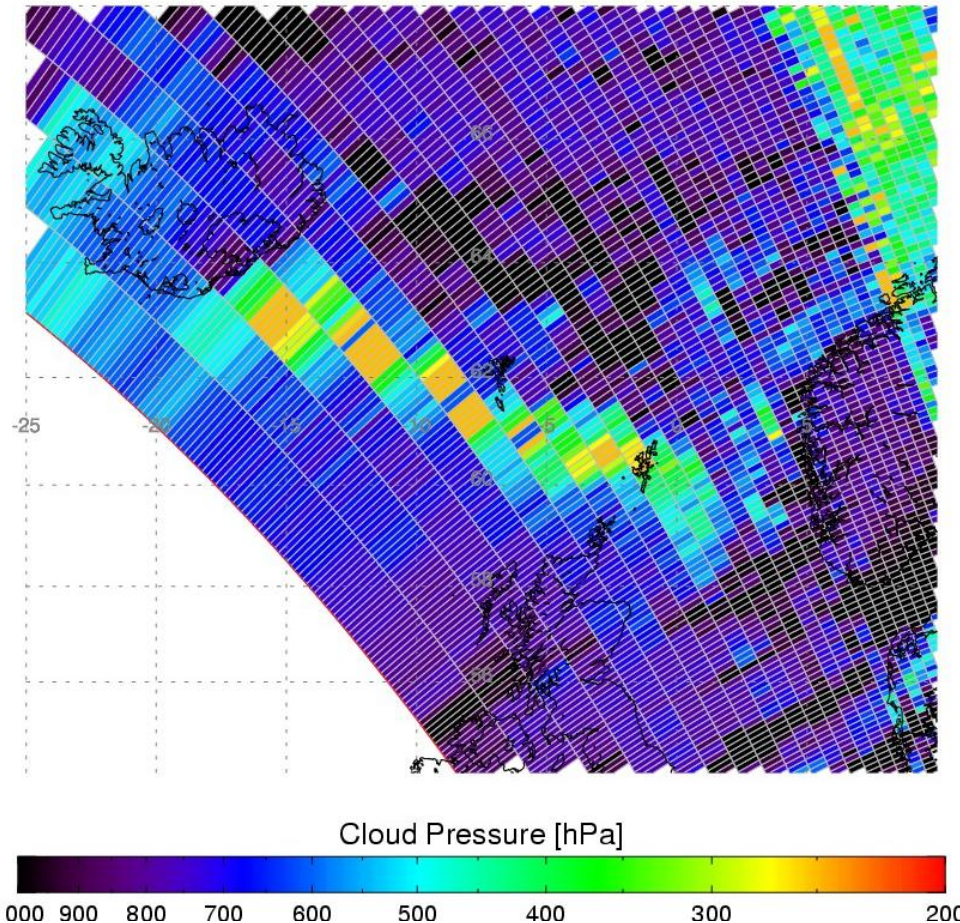


- Typical concentrations were $\sim 2\text{-}4 \text{ mg m}^{-3}$

Eyjafjallajökull eruption plume – April 15, 2010



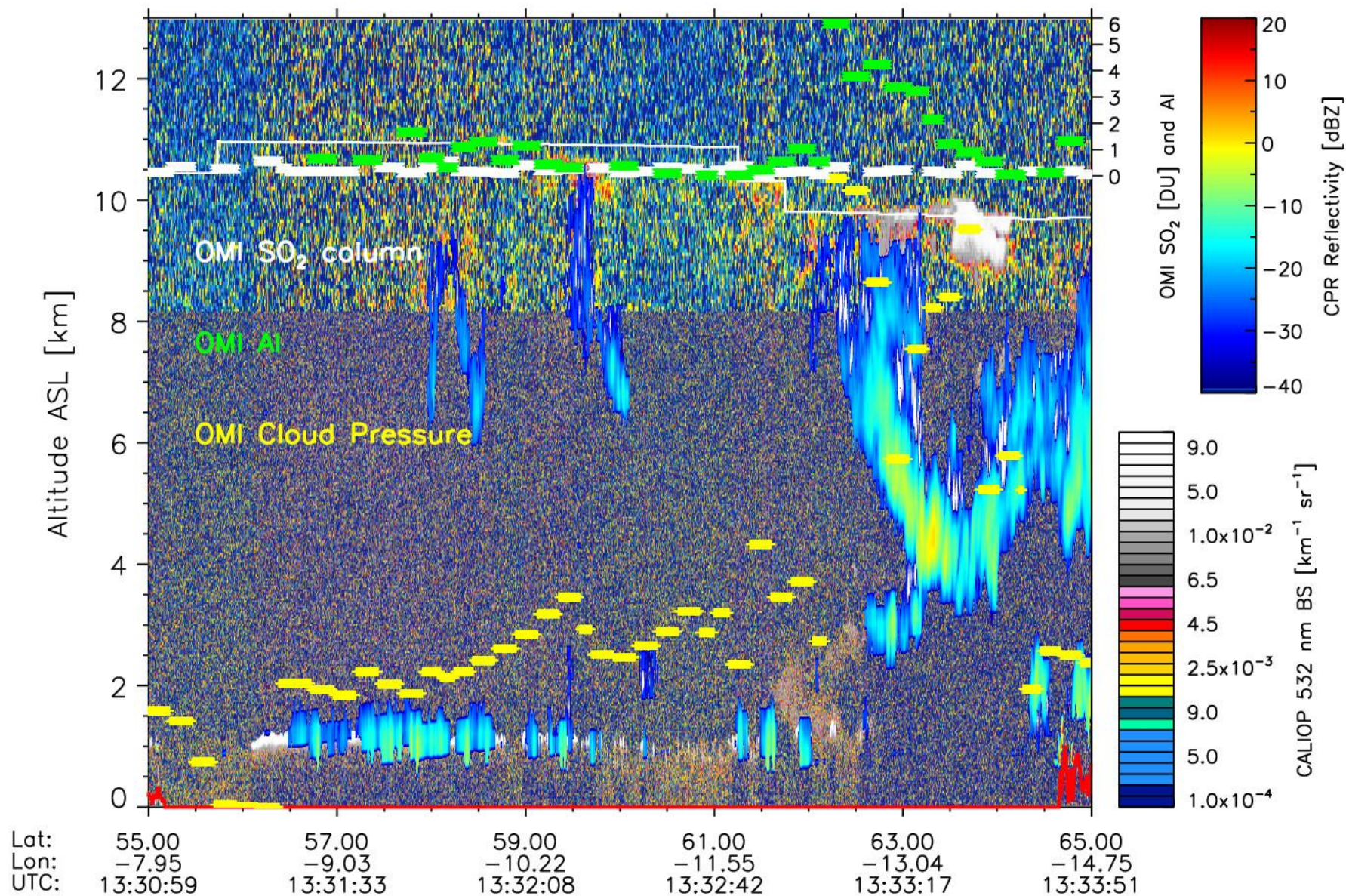
OMI SO₂ column



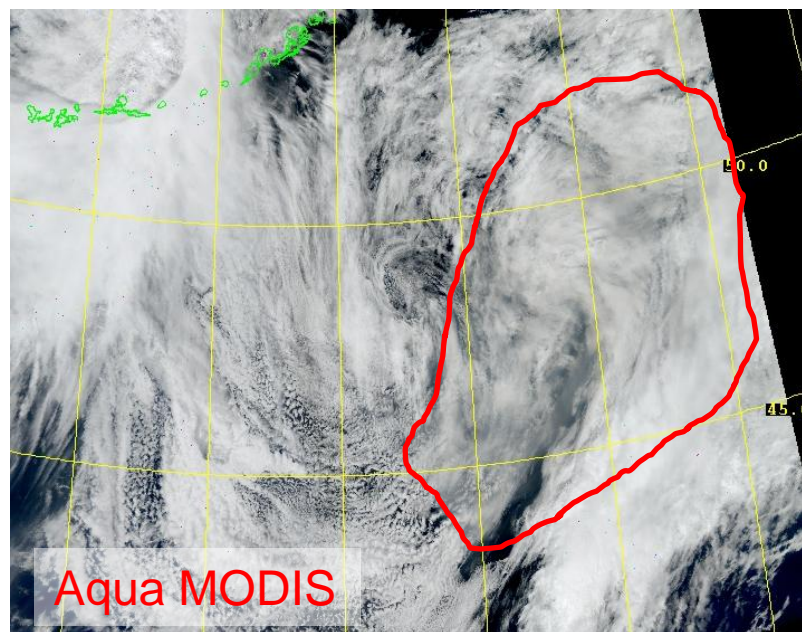
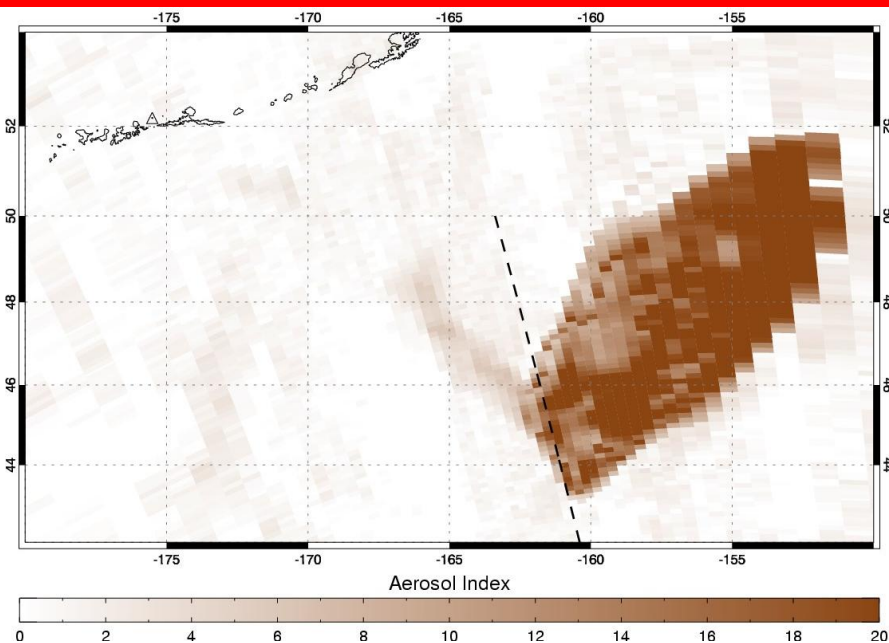
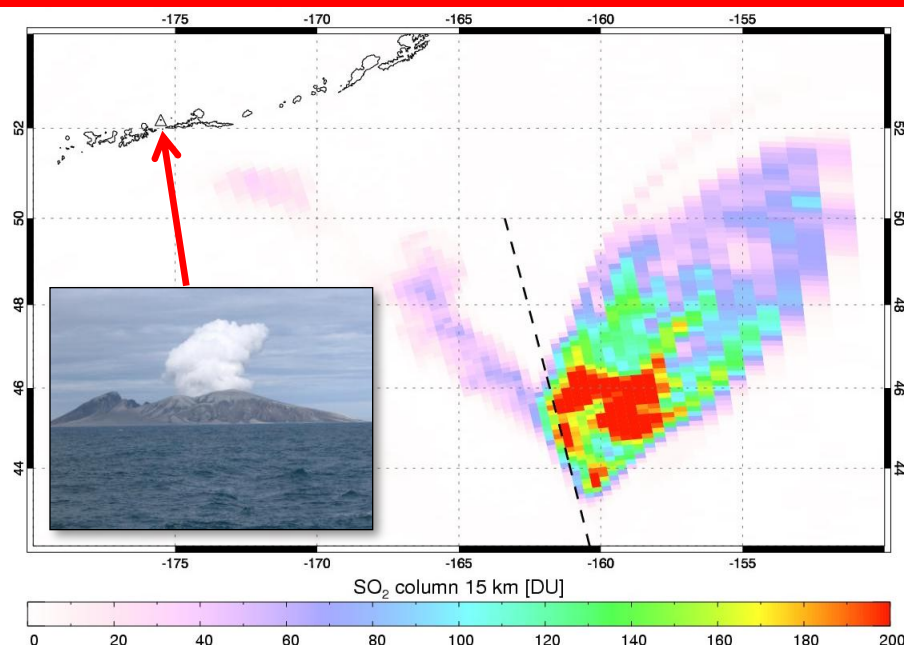
OMI Cloud Pressure

- NB: OMI row anomaly coincides with CALIPSO/CloudSat track

CALIPSO + CloudSat + OMI: April 15, 2010



A-Train observations: Kasatochi, August 9, 2008

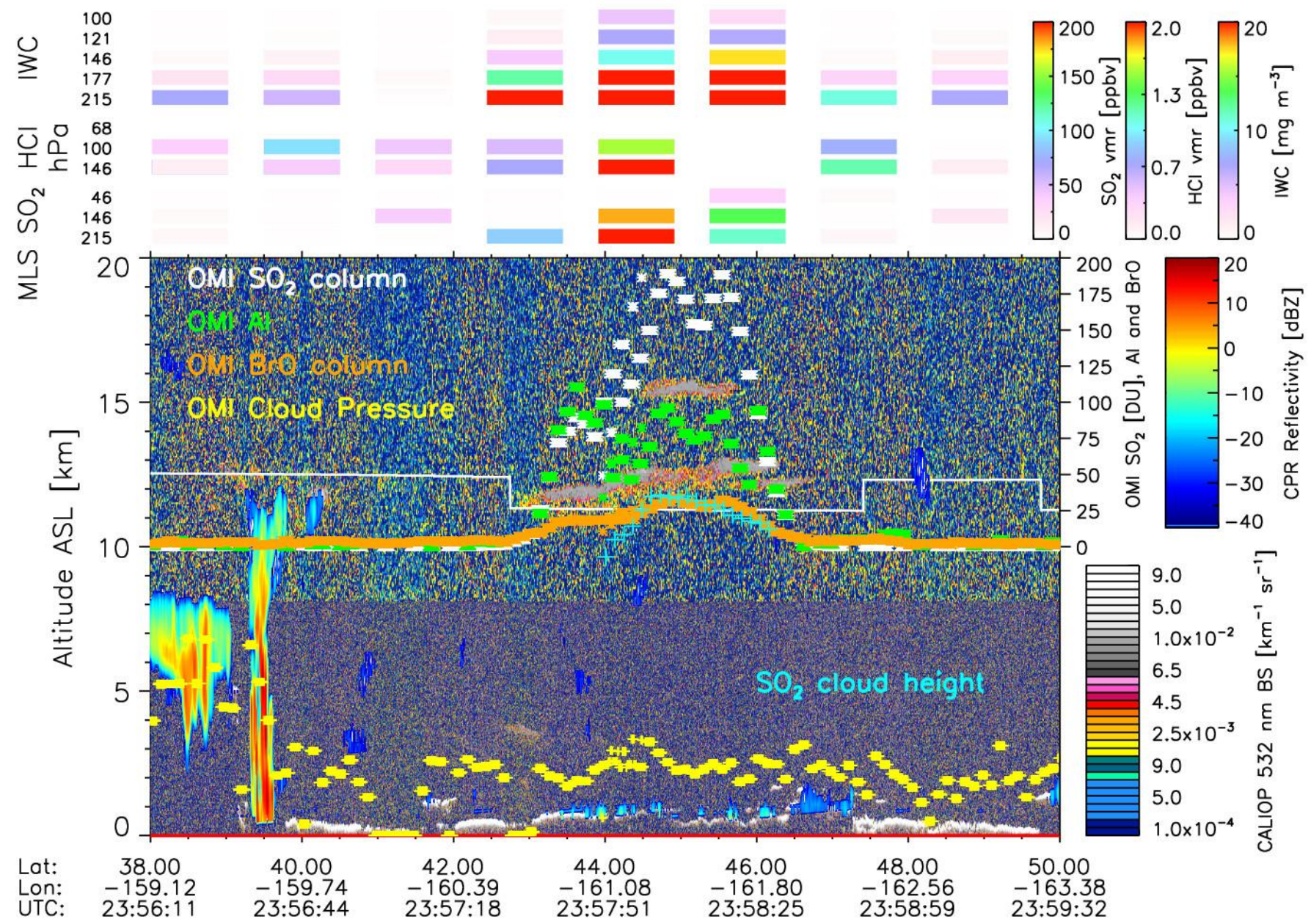


- Largest volcanic SO₂ emission since 1991 (~2 Tg)
- Negligible climate impact

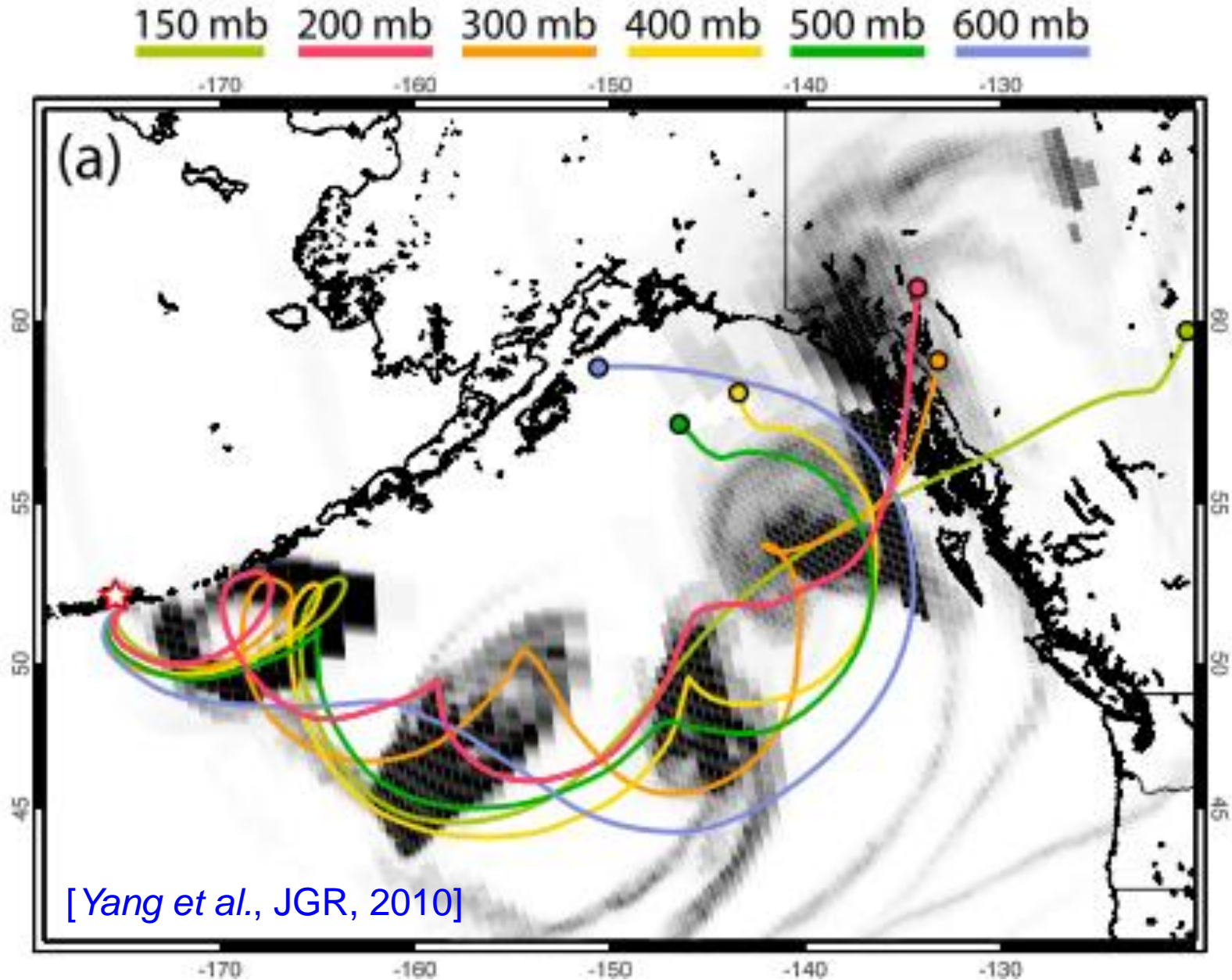
JGR Special issue

http://www.agu.org/journals/jd/special_sections.shtml?collectionCode=VOLCANOES1&journalCode=JD

A-Train observations: Kasatochi, August 9, 2008

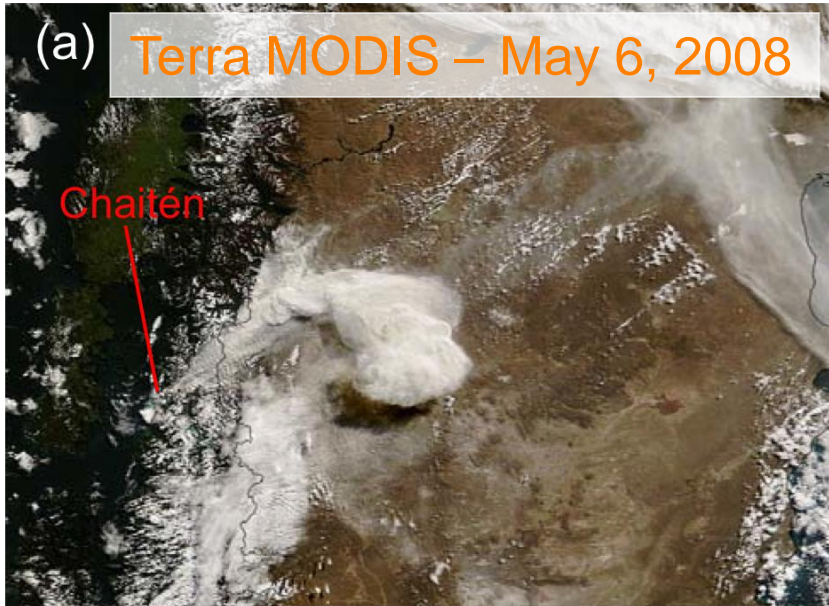


Forward trajectories for the Kasatochi volcanic cloud



A-Train observations: Chaitén (Chile), May 2008

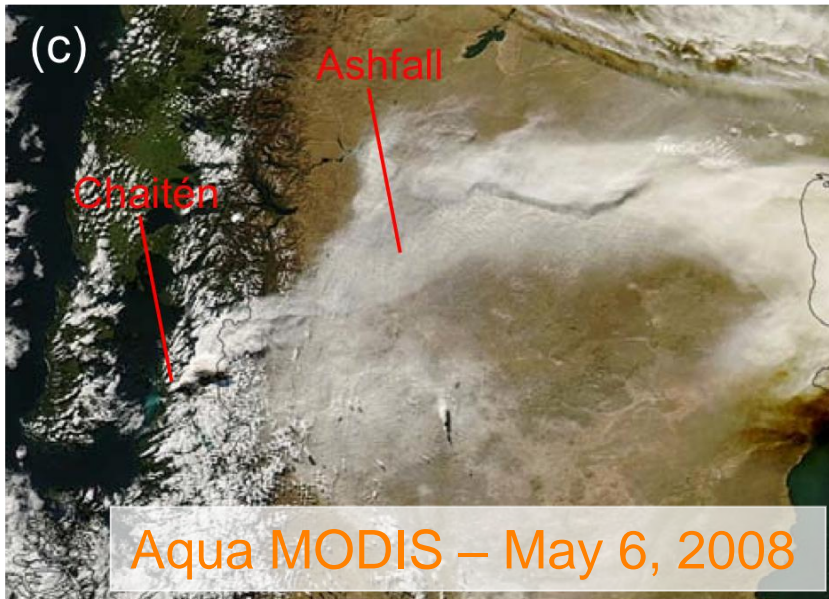
(a) Terra MODIS – May 6, 2008



[Carn *et al.*, EOS, 2009]



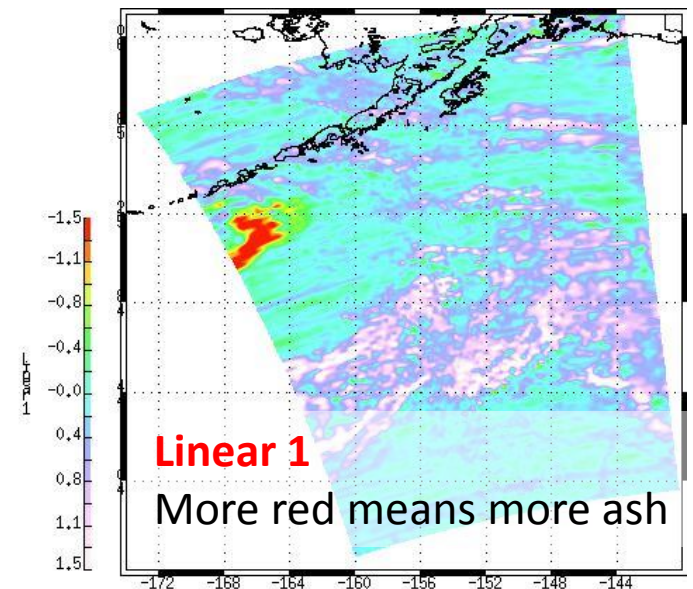
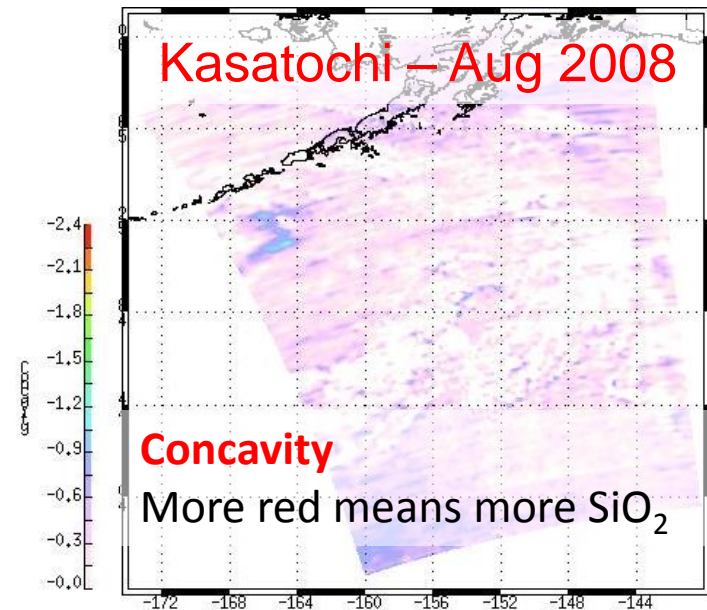
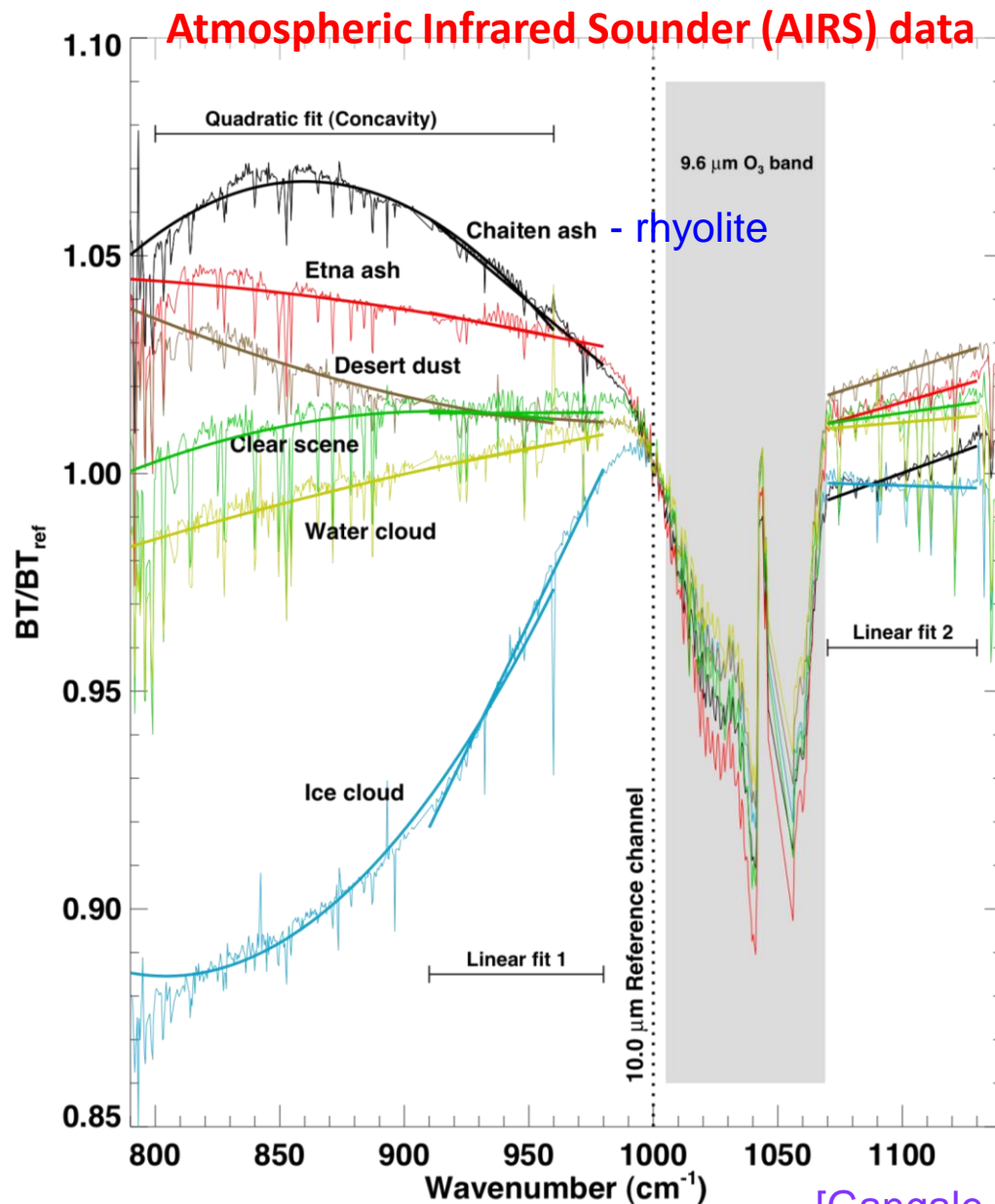
(c) Aqua MODIS – May 6, 2008



- Eruption at ~0800 local time on 6 May
- High wind shear environment

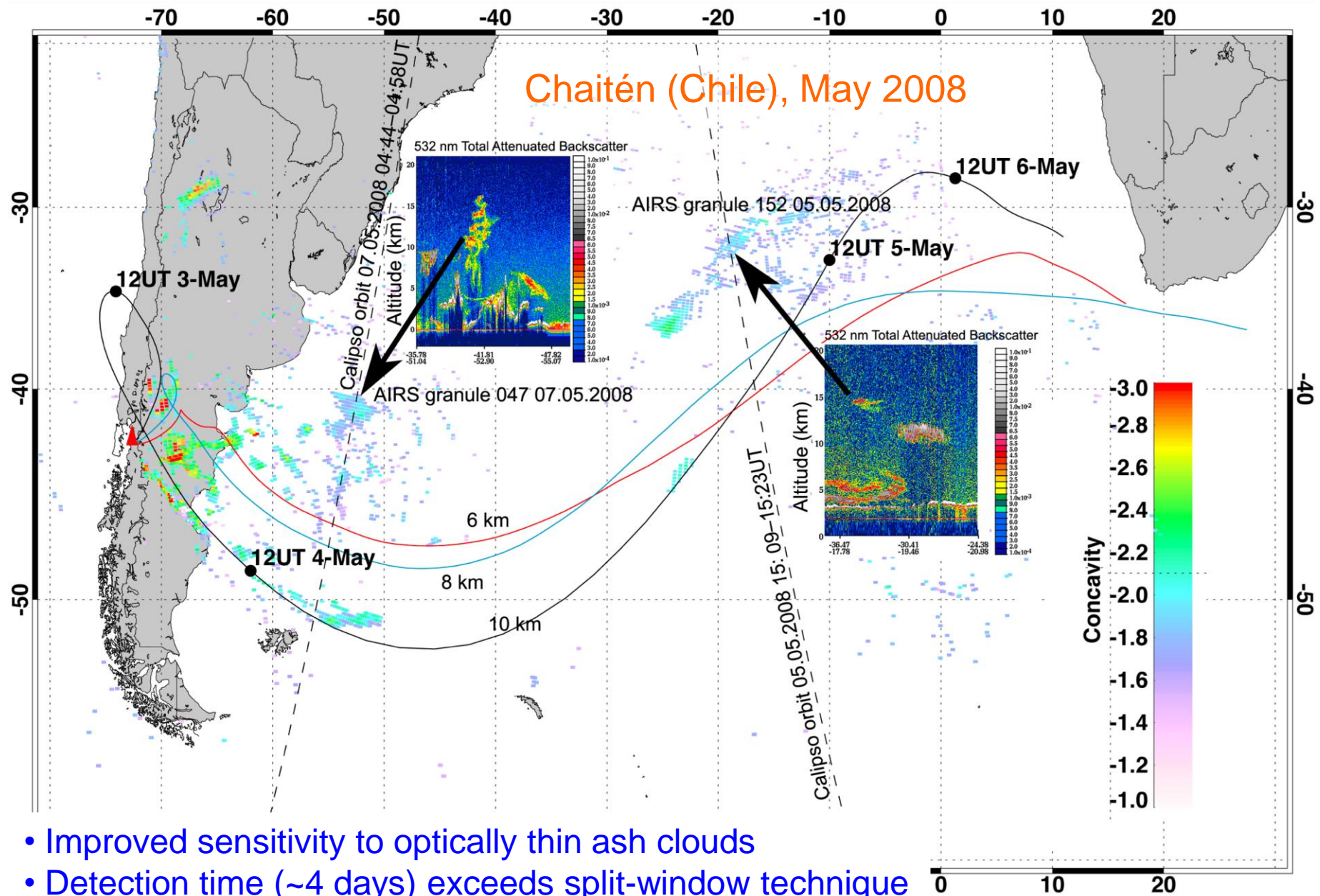


IR ash composition retrievals – the ‘Concavity’ signature



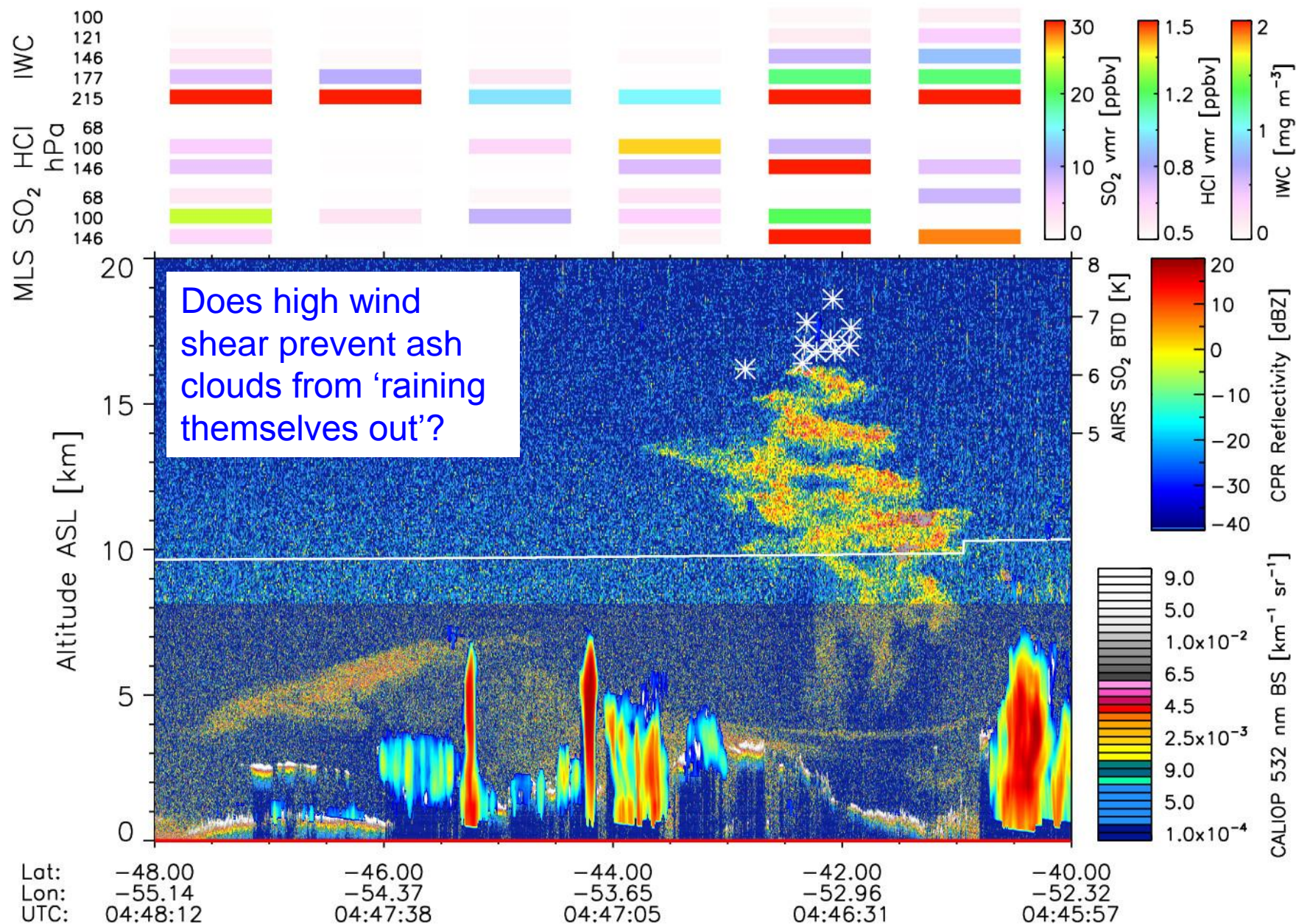
[Gangale *et al.*, RSE, 2009]

Volcanic ash tracking with the AIRS concavity algorithm

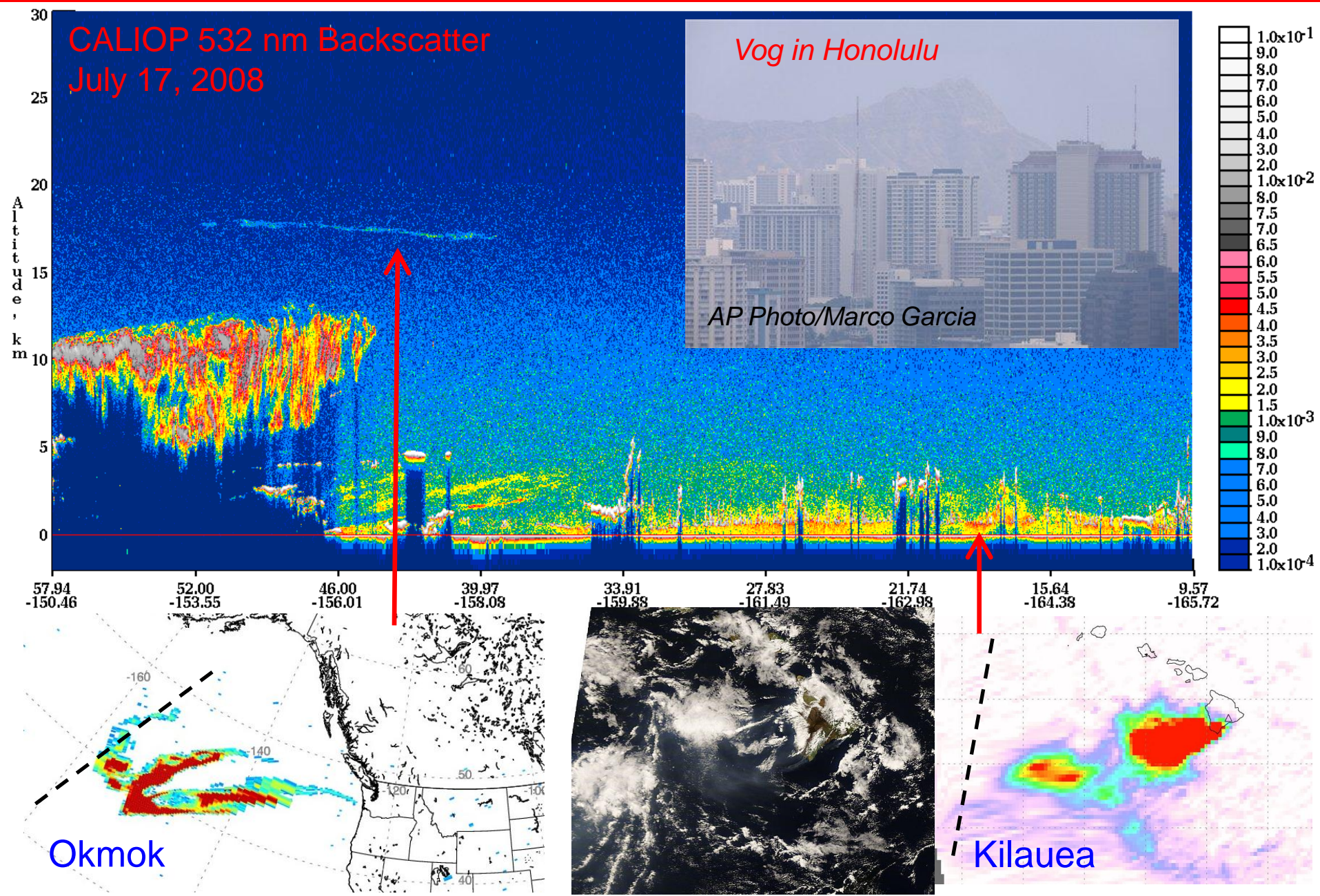


- Improved sensitivity to optically thin ash clouds
- Detection time (~4 days) exceeds split-window technique

A-Train observations: Chaitén (Chile), May 7, 2008



Monitoring tropospheric volcanic plumes with CALIPSO

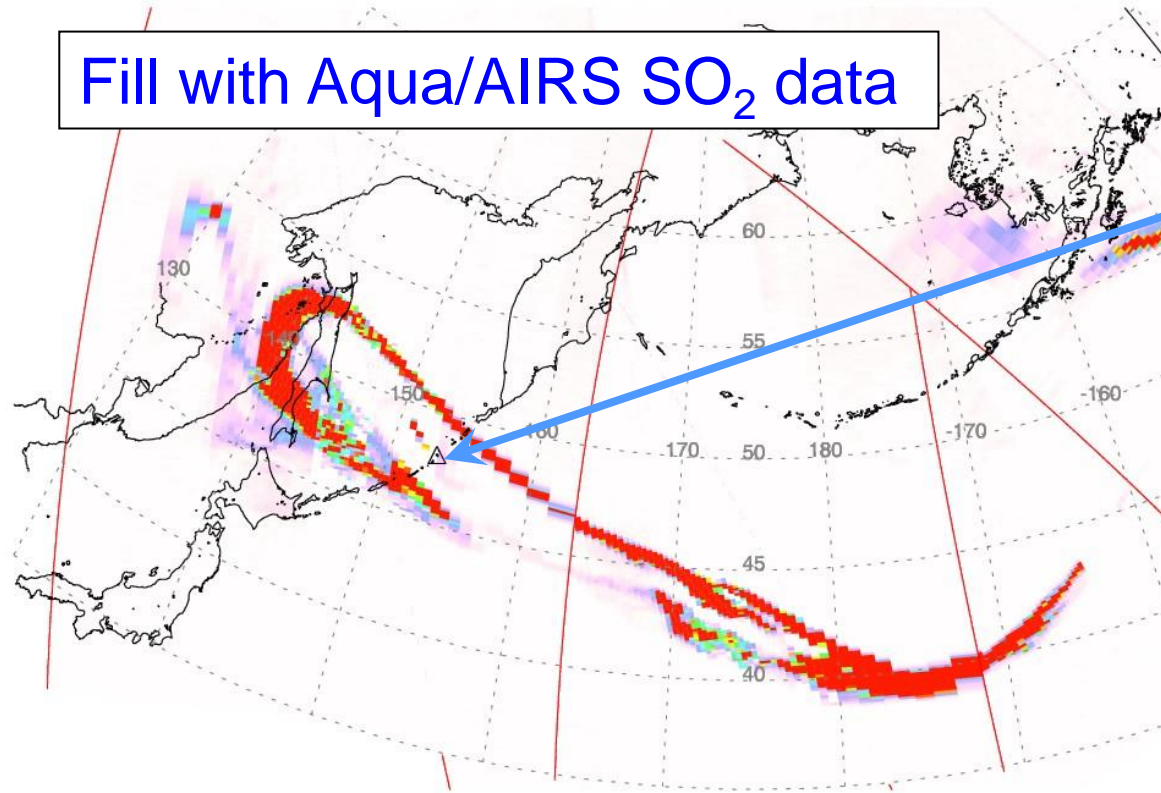


Sarychev Peak (Kurile Is) eruption

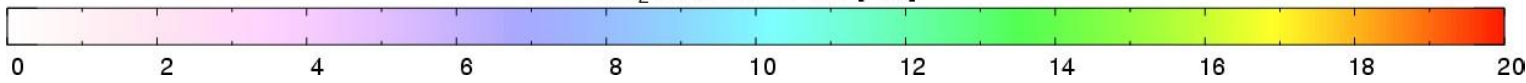
Aura/OMI+Aqua/AIRS - 06/17/2009 00:11-22:43 UT

SO₂ mass: 847.965 kt; Area: 2537886 km²; SO₂ max: 194.59 DU at lon: -177.23 lat: 39.83 ; 01:51UTC

Fill with Aqua/AIRS SO₂ data



SO₂ column 15 km [DU]

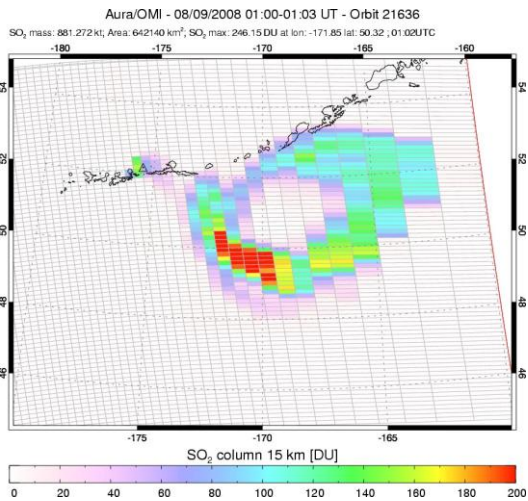


Astronaut photo from ISS, 14 June

- Previous eruptions in 1986-89
- 2nd large NH stratospheric SO₂ injection (≥ 1 Tg) in a year, after the August 2008 Kasatochi eruption (Aleutian Is)
- Timing near summer solstice increases aerosol radiative (cooling) effect
- Major disruption to aviation

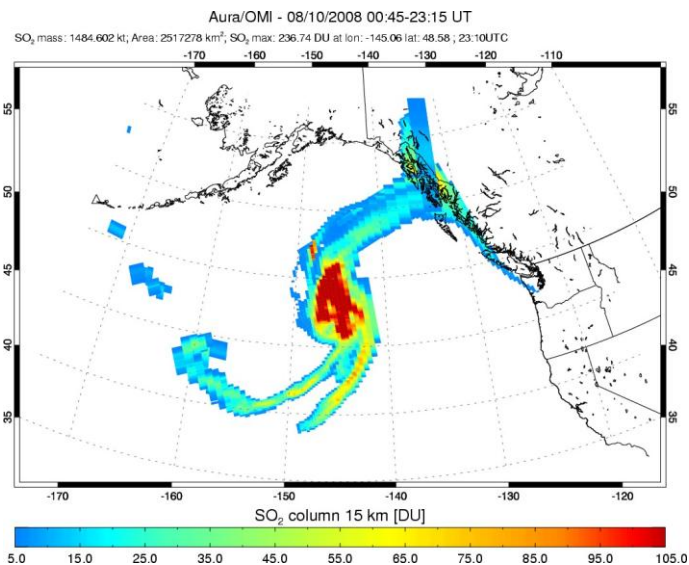
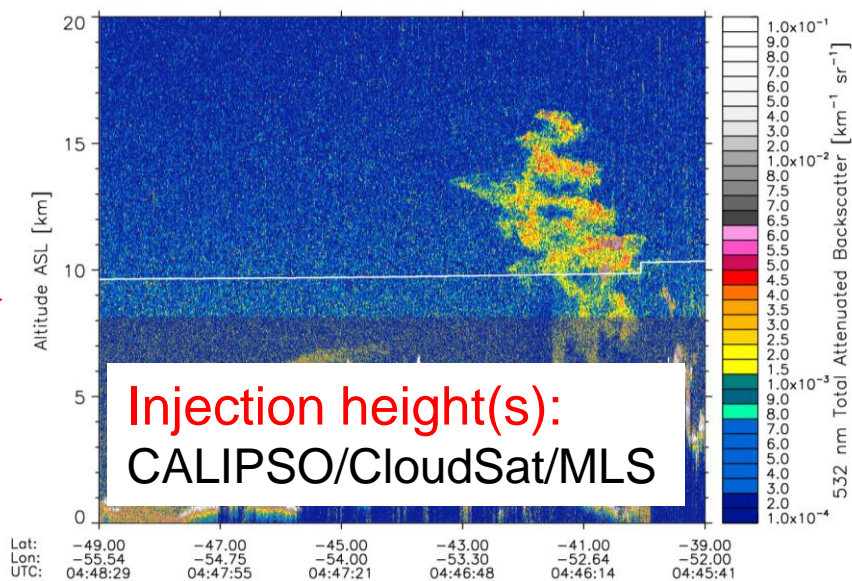
• A-Train synergy compensates for data gap and improves SO₂ loading measurements

Hypothetical A-Train eruption monitoring system

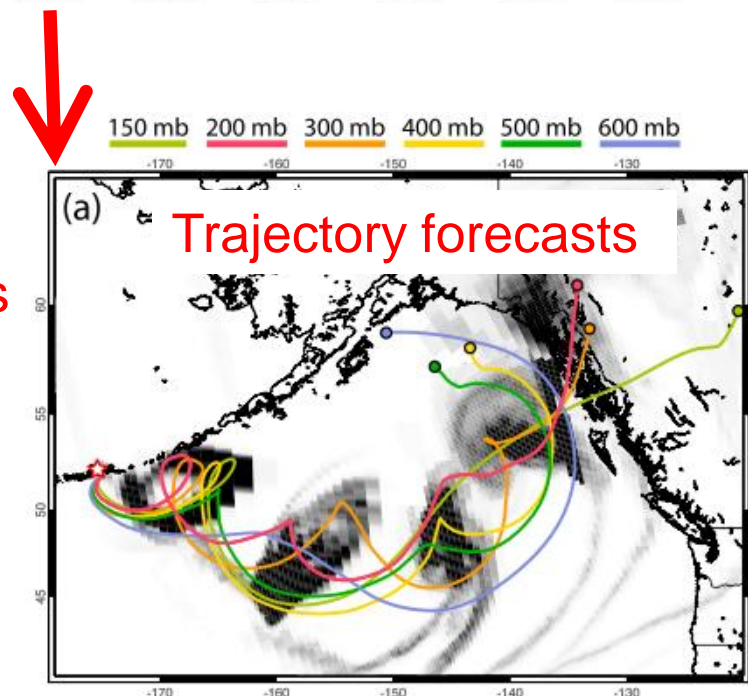


Eruption detection:
SO₂ (OMI, AIRS); Thermal IR (MODIS)

Key issues:
Data latency
Spatial coverage



Compare with
SO₂/ash maps



Summary

- The A-Train is providing unprecedented observations of the vertical distribution of trace gases, aerosols and hydrometeors in volcanic clouds
- New insights into ashfall processes and stratospheric aerosol evolution in volcanic clouds are anticipated (see *talk by Mike Fromm*)
- Measurements of ash cloud altitude and thickness (e.g., by CALIPSO) are of prime importance for aviation hazard mitigation
- Currently, data latency of most A-Train products (and spatial coverage of the active sensors) is the main impediment to operational application for aviation hazard mitigation
- The A-Train greatly facilitates validation/intercomparison of satellite data products (e.g., SO₂ column measurements)

Acknowledgments:

